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# RESEARCH MEMORANDUM

## PERFORMANCE AT SIMULATED HIGH ALTITUDES OF A PREVAPORIZING ANNULAR TURBOJET COMBUSTOR HAVING LOW PRESSURE LOSS

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NATIONAL ADVISORY COMMITTEE
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# PERFORMANCE AT SIMULATED HIGH ALTITUDES OF A PREVAPORIZING ANNULAR TURBOJET COMBUSTOR HAVING LOW PRESSURE LOSS

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## SUMMARY

An investigation was conducted to reduce the pressure drop in an experimental combustor designed to operate with high efficiencies at high altitude. The combustor utilized a previously designed prevaporizing fuel system that supplied vapor fuel to the injectors for high-altitude operation. The combustor geometry incorporated a streamlined combustor inlet section, scoops for primary-air admission, and longitudinal U-shaped channels for secondary-air admission. The combustor was designed to fit into a one-quarter sector of an annular housing with an outside diameter of 25.5 inches, an inside diameter of 10.6 inches, and a combustor length of approximately 23 inches. The performance of the combustor was investigated at simulated high-altitude flight conditions corresponding to operation in a 5.2-pressure-ratio engine at a flight Mach number of 0.6. The effectiveness of the fuel prevaporizer was examined qualitatively by comparing the performance of the combustor with gaseous propane fuel and liquid and preheated JP-4 and JP-5 fuels.

The total-pressure loss of the experimental combustor was 2 to 4 percent at a reference velocity of 80 feet per second, as compared with a total-pressure loss of 4 to 6 percent for most current production model combustors. Combustion efficiencies of 98, 88, and 81 percent were obtained with JP-4 fuel at conditions simulating rated engine speed operation at altitudes of 56,000, 70,000, and 80,000 feet, respectively. Pressures of 15, 8, and 5 inches of mercury absolute in the combustor were obtained for these altitudes with the 5.2-pressure-ratio and the low flight Mach number conditions. Combustion efficiencies obtained with gaseous propane were similar to those obtained with JP-4, indicating that sufficient fuel vaporization was obtained with this fuel under normal operating conditions. Increasing the airflow rate to 69 percent above current practice at an altitude of 56,000 feet or using the less volatile JP-5 fuel in the combustor had a detrimental effect on combustion efficiency. The losses in efficiency were recovered, in both cases, when the temperature of the fuel admitted to the prevaporizer was increased to 250° or 350° F. While these results indicate a need for greater

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prevaporizer capacity in the experimental combustor for operation with low-temperature fuel (80° F), in most aircraft applications fuel is delivered to the combustor at temperatures in the range of 250° to 350° F.

At the test conditions investigated the combustor exhaust-temperature profile followed the pattern generally desired at the turbine position.

## INTRODUCTION

High-altitude operation of turbojet engines is frequently accompanied by serious losses in combustion efficiency. It has been shown that at high altitudes preheating the liquid fuel before injection into the combustion chamber increases combustion efficiency significantly; use of a gaseous fuel results in even greater gains in efficiency (ref. 1). Research on an experimental turbojet combustor that incorporated a liquid-fuel prevaporizer is reported herein.

A prevaporizing combustor incorporating a fuel system, designed to supply liquid fuel at sea level and low altitudes, preheated fuel with an increasing vapor content up to a simulated altitude of 56,000 feet, and 100-percent vaporized fuel at higher altitudes, is described in reference 2. The prevaporizing coils of this combustor were located at the downstream end of the primary zone prior to the entry of secondary air. This location was chosen for two reasons: (1) to avoid quenching effects in the burning zone due to cold prevaporizer walls, and (2) to minimize pressure loss due to the coils by placing them in a low mass-flow region. The combustor operated with a high combustion efficiency. While the pressure losses were of the same magnitude encountered in current production engines, redesign of the combustor liner was undertaken to explore the possibilities of reducing pressure losses.

The reduced pressure-loss combustor had an air-entry pattern similar to that of model 30 of reference 2 which incorporated the prevaporizing system described in reference 2. Design modifications to reduce the pressure loss were directed toward improvement of the combustor-liner geometry with respect to the combustor housing and provision for adequate open air-entry area. The fuel manifold and the upstream primary zone walls were integrated into an annular, symmetrical wedge arrangement that improved the entrance air diffusing passages. Modification of the primary zone to obtain low pressure loss resulted in decreasing the air-entry orifice coefficients, which in turn reduced the mass flow into the primary region. The required primary flow was obtained by use of special airscoops that separated a small fraction of the air from the mainstream, and then admitted this air fraction in a predetermined manner.

The design of the secondary zone required efficient mixing of the cold and hot gases with minimum mixing losses. The principle of "interleaving" hot and cold gas zones, as discussed in reference 3, was used in the combustor. The walls of the secondary zone were made up of a series of U-shaped channels extending from the primary wall to the outer housing. The longitudinal slots between the channels formed air admission ports with low entrance loss characteristics (ref. 4).

These features, incorporated into a quarter-sector annular combustor configuration, were investigated in a connected duct test system. High-altitude flight conditions were simulated assuming a turbojet engine with a compressor pressure ratio of 5.2 operating at 0.6 flight Mach number. Combustion efficiency, outlet temperature profile, combustor pressure loss, and prevaporizer performance data were obtained with two liquid-hydrocarbon fuels and compared with similar data obtained with gaseous propane at selected flight altitudes up to 80,000 feet. One of the liquid hydrocarbons used was the current jet fuel JP-4; the other, JP-5, is representative of a fuel having better volatility characteristics for supersonic flight applications (ref. 5).

## APPARATUS

### Installation

The combustor installation (fig. 1) was similar to that of reference 2. The combustor-inlet and -outlet ducts were connected to the laboratory-air-supply and low-pressure-exhaust systems, respectively. Airflow rates and combustor pressures were regulated by remote-controlled valves located upstream and downstream of the combustor. Gaseous propane was supplied from an 800-gallon pressurized tank with automatic controls preset to deliver the prescribed fuel-vapor requirements. Liquid fuel was supplied from individual barrels connected to a suitable pumping system. The inspection data for MIL-F-6524C, grades JP-4 and JP-5 jet fuel are presented in table I. The desired combustor-inlet air and fuel temperatures were obtained by means of electric preheaters.

### Instrumentation

Airflow was metered by a sharp-edged orifice (fig. 1) installed according to ASME specifications. The liquid fuel-flow rate was metered with a calibrated rotameter, and the vapor fuel-flow rate, with a calibrated sharp-edged orifice. Thermocouples and pressure tubes were located at the combustor-inlet and -outlet instrument stations indicated in figure 1. The number, type, and position of these instruments at each of the three stations are indicated in figures 2(a) to (c). The combustor-outlet thermocouples (station 2) and pressure probes (station 3) were located at

centers of equal area in the duct. The design of the individual probes is shown in figures 2(d) to (h). Manifolded upstream total-pressure probes (station 1) and downstream static-pressure probes (station 3) were connected to absolute manometers; individual downstream total- and static-pressure probes were connected to banks of differential manometers. The chromel-alumel thermocouples (station 2) were connected to a self-balancing, recording potentiometer.

## Combustor

The experimental combustor incorporated a fuel-prevaporizing system developed for a previous experimental combustor (model 30, ref. 2). The heat-transfer area of the prevaporizer was contained in three coils of the type shown in figure 3. Liquid fuel was supplied to the three prevaporizing coils, which were connected in series. The vaporized fuel was returned to the fuel manifold, where it was distributed to the fuel nozzles. The total heat-transfer surface area was 70.9 square inches, which, from previous calculations and experimental data, was considered sufficient to vaporize all of a JP-4 type fuel needed for rated-speed operation at 56,000 feet.

Design considerations. - The design of the final combustor model was essentially in two steps: (1) initial design of the combustor geometry to ensure low pressure losses, and (2) "cut-and-try" modification of the air-entry areas and fuel injectors to obtain high combustion efficiency. The combustor geometry was designed to streamline the flow of air past the combustor and maintain an adequate hole area. The cross-sectional view of the combustor is shown in figure 4. An annular wedge was installed in the inlet-diffuser section to divide the air between the inner and outer walls. The wedge became an integral part of the combustor, forming the fuel manifold and part of the primary-zone wall. The wedge angle and position were selected to integrate the combustor liner and combustor housing into an improved inlet-diffuser unit. However, a consideration of boundary-layer separation, available length, combustor-housing configuration, passage depth, and hydraulic radius of the combustion space necessitated a compromise design configuration. The walls of the primary zone downstream of the wedge were parallel. The secondary zone was composed of a series of U-shaped channels that extended from the primary-zone walls to the combustor housing. The longitudinal slots formed by the channels provided an effective means of controlling the outlet-temperature distribution by "interleaving" the hot combustion gases and the cold dilution air.

Combustor development. - Modification of the initial low-pressure-loss combustor design was directed toward improving the combustion efficiency. The modification included alterations of the combustor air-entry

holes, addition of various scoop arrangements for the primary entry holes, and the use of various fuel nozzles. The various fuel nozzles used are tabulated as follows:

| Nozzle designation[a] | Description |
|---|---|
| F | Extended fan spray nozzles, $1\frac{1}{2}$ in. long |
| I | Simple sharp-edged orifice, 7/64-in. diam. |
| K | Simple sharp-edged orifice, 1/8-in. diam. |
| L | Simple sharp-edged orifice (with simple swirl generator), 1/8-in. diam. |
| N | Simple sharp-edged orifice, 9/64-in. diam. |
| O | Simple sharp-edged orifice, 11/64-in. diam. |
| P | Simple sharp-edged orifice (with simple swirl generator), 9/64-in. diam. |
| Q | Simple sharp-edged orifice (with simple swirl generator), 11/64-in. diam. |

[a]The fuel nozzle designation is a continuation of the system used in ref. 2.

The combustor modifications that led to the final design are as follows:

| Combustor model[a] | Description |
|---|---|
| 31K | Original low-pressure-loss design |
| 32K | Secondary channels modified |
| 33K,34I,34N | Primary-zone holes modified |
| 35N | Continuous scoops added to top and bottom of primary-zone walls |
| 36N,37N | Primary-zone holes modified |
| 38I | Continuous scoops removed, primary-zone holes modified |
| 39I,39N,39O,39F,39P | Primary-zone holes modified |
| 40K,41K,41L | Nozzle placement changed, combustor faceplate modified |
| 42L,43L | Primary-zone holes modified |
| 44L | Large continuous scoops added in primary-zone walls |
| 45L,45K,45Q | Channel open area decreased |
| 47N,47L | Continuous scoops were removed from model 44, and two 9/16- by 2-in. scoops approximately 6 in. long were added to reinforce primary zone. Small individual scoops were added for two selected rows of primary-zones holes. |

[a]The combustor model number is a continuation of the model designations used in ref. 2. Letter designation indicates the fuel nozzles used in a particular model.

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Final configuration. - The air-entry-hole pattern for model 47 combustor is shown in figure 5(a). The ratio of the accumulated hole area along the combustor length to the total hole area is shown as a function of combustor length in figure 5(b). Data from model 30 (ref. 2) are included for comparison. Note that these curves represent the proportioning of the hole area and not necessarily the proportioning of the air admitted along the combustor. The total open areas for these two combustors are quite different (model 47, 95.9 sq in. and model 30, 69.4 sq in.); in addition, the scoops in the primary zone of model 47 are expected to change the discharge coefficients of the individual holes 4180
(ref. 6).

A photograph of combustor liner model 47 and an artist's sketch of the assembled combustor is shown in figure 6. As shown in the photograph (fig. 6(a)), a variety of scoops was used in model 47. The different shapes were selected purely for convenience in fabrication, and the particular scoop shape is not considered significant. The capture area of the scoops, however, was considered critical and was based on the area required for maximum flow through the hole assuming a 0.6 orifice discharge coefficient for the hole.

## PROCEDURE

The test conditions used for the investigation are as follows:

| Test condition | Combustor-inlet total pressure, $P_i$, in. Hg abs | Combustor-inlet total temperature, $T_i$, $^{\circ}F$ | Airflow rate per unit area[a] $w_a/A$, lb/(sec)(sq ft) | Simulated flight altitude in reference engine at cruise speed, ft |
|---|---|---|---|---|
| A | 15 | 268 | 2.14 | 56,000 |
| B | 8 | 268 | 1.14 | 70,000 |
| C | 5 | 268 | 0.714 | 80,000 |
| E | 15 | 268 | 3.62 | 56,000 |

[a]Based on maximum combustor cross-sectional area of 0.73 sq ft.

Test conditions A, B, and C represent three simulated flight conditions for a reference turbojet engine with a 5.2 pressure ratio at a flight Mach number of 0.6. Cruise speed was taken as 85 percent of the rated rotor speed. One additional condition, test condition E, was selected to represent an airflow rate 69 percent above that required in the reference engine. At each test condition combustion efficiencies and pressure-loss data were recorded for a range of fuel-air ratios.

Propane was used as the fuel for the combustor development. The final experimental combustor, model 47L, was operated with gaseous propane, the current JP-4 jet fuel, and the JP-5 jet fuel with low volatility.

Combustion efficiency was computed by the method of reference 7 as the percentage of the ratio of the actual to the theoretical increase in enthalpy from the combustor-inlet to the combustor-outlet instrumentation plane (stations 1 and 2). The arithmetical mean of the 30 thermocouple outlet indications was used to obtain the value of the combustor-outlet enthalpy for the experimental combustor configuration. The bulk temperatures as determined from thermocouple indications are subject to numerous errors due to mass distribution and heat-transfer effects; however, no corrections were applied to the data presented in this report.

A qualitative indication of the errors involved at the test conditions investigated was obtained from two independent measurements of combustion efficiency. Efficiencies calculated from indicated thermocouple readings were compared with (1) efficiencies calculated from bare-wire chromel-alumel thermocouple readings corrected for conduction and radiation errors according to the procedure recommended in reference 8 and corrected for nonuniform mass-flow distribution, and (2) efficiencies determined from sampling and analysis of unburned constituents in the exhaust gas.

The thermocouple correction equations require information that cannot be obtained accurately in the experimental combustor test rig used. An approximation was attempted for a limited number of data points by measuring wall temperatures at the instrumentation plane and assuming no flame radiation at the low pressures. The results obtained for combustor model 43L at an outlet temperature of approximately 1450° F for three of the test conditions are as follows:

| Condition | Combustion efficiency, percent | |
|---|---|---|
| | Calculated | Indicated |
| A | 100.4 | 99.2 |
| C | 96.0 | 83.6 |
| E | 100.8 | 99.7 |

It is apparent that at the low-pressure condition (C) the combustion efficiency from indicated thermocouple readings was low.

An exhaust-gas sample was obtained by using a water-cooled sampling probe with ports located in the same position as the thermocouples. Two disadvantages in using exhaust-gas sampling in full-scale combustors are (1) small percentages of unburned products are difficult to determine accurately from a small sample, and (2) it is difficult to obtain a representative sample because of unburned fuel droplets passing through

the combustion zone. The accuracy of the method was improved by using a precision gas analyzer technique in conjunction with vapor fuel in the combustor (gaseous propane was used with a fuel-air ratio of approximately 0.020). Combustion efficiencies were determined with experimental combustor model 45Q at test condition C (5 in. Hg abs.; runs 35 and 36 in table II). Analysis of the exhaust-gas sample showed that the unburned constituent was mainly carbon monoxide with traces of hydrogen and methane present. No trace of unburned propane was detected. The efficiency computed by gas analysis was 87 percent; the efficiency calculated from the thermocouple indications was 79 percent. These data agree qualitatively with the results obtained by thermocouple correction, in that the efficiency calculation from indicated thermocouple readings was low compared with the efficiency obtained from exhaust-gas analysis.

At the low pressures, combustion efficiency indications were low. At the higher pressures corresponding to most of the test-conditions compensating factors, such as increased radiation from the flame and increased convective heat transfer, enter into the temperature measurements, and the difference between the indicated and corrected efficiency was small. The limited data obtained indicate that the combustion efficiencies reported at the low-pressure condition (C) may be low by as much as 10 percent; however, the qualitative comparison between the various combustor models and the differences among fuels is considered reliable.

The radial temperature distribution at the combustor outlet (station 2) was determined for a temperature rise across the combustor of approximately 1180° F, which corresponds to the required value for a rated engine speed operation in the reference turbojet engine at altitudes above the tropopause. The radial temperature indications were obtained from the six thermocouple rakes (fig. 2). The total-pressure loss was computed as the dimensionless ratio of the total-pressure loss to the combustor-inlet total pressure. Thirty individual total pressure readings were averaged to obtain the total pressure at the combustor outlet. Combustor reference velocities were computed from the air mass-flow rate, the combustor-inlet density, and the maximum combustor cross-sectional area.

## RESULTS AND DISCUSSION

### Combustor Development

The experimental combustor configurations were first operated with gaseous propane. Gaseous propane facilitated preliminary operation since it represented the optimum condition (100-percent vapor) that could be obtained with prevaporized JP-4 fuel. The experimental data obtained during the investigation are presented in table II.

Combustion efficiencies obtained with propane fuel in the model 31K combustor (initial design) are presented in figure 7 for a range of fuel-air ratios at test conditions B and C. It is apparent that the combustor operated with a fuel-rich primary zone since the efficiencies decreased rapidly with an increase in fuel-air ratio, and that the temperature rise required for rated speed was not obtainable. Early modifications were therefore aimed at directing more air into the primary zone, and eliminating severe hot spots in the outlet-temperature profile. The fuel-rich primary zone was anticipated since it is shown in reference 4 that the over-all coefficient of the primary zone is reduced as the pressure drop is decreased.

Efficient burning in the primary combustion zone requires control of fuel spray as well as air-entry distribution. Data obtained during the test program with successive combustor configurations substantiated the importance of selecting an optimum fuel-injector system. In figure 8, the combustion efficiencies are presented for combustor model 45 with fuel nozzles L, K, and Q at test condition C using propane fuel. Efficiency differences as high as 15 percent (nozzles L and K) were obtained at this operating condition. These differences were due to the fuel spray pattern. Nozzle L contained a swirl generator; nozzle K did not. Smaller differences (5 percent) were obtained when the swirl generators were installed and the fuel-nozzle orifice was enlarged from 1/8 to 11/64 inch in diameter (nozzles L and Q).

In combustor model 45 the five fuel nozzles were placed directly in line with the longitudinal rows of primary-air holes. In a preceeding combustor (model 39) alternate fuel and air zones were established circumferentially in the primary zone by placing the fuel nozzles between the rows of primary air holes. The combustion efficiencies obtained with combustor model 39P are shown in figure 9. Although this combustor operated with a fuel-rich primary, the combustion efficiency was over 80 percent up to a fuel-air ratio of 0.019 at test condition C. This efficiency compares favorably over most of the fuel-air ratio range with the efficiencies obtained with combustor model 45, as shown in figure 8. The present research indicates, then, that a particular circumferential location of the fuel nozzles relative to the air holes may not be necessary to achieve high efficiencies. In any case, however, considerable modification of the primary zone may be required to obtain high performance. The later combustor configurations, models 45, 46, and 47, were operated with fuel nozzles in line with air holes.

## Performance of Final Combustor Model 47L

Combustion efficiency with propane. - The combustion efficiencies obtained with the model 47L combustor operating on propane fuel are presented in figure 10 for the test conditions A, B, C, and E. Data are

presented for the gaseous fuel (1) injected directly into the combustor with no prevaporizer, and (2) injected with the prevaporizing equipment. Data obtained with propane in combustor model 30 (ref. 2), which was the best previous combustor configuration, are included for comparison. The combustion efficiencies for the three curves vary by approximately 5 percent. The efficiencies with the prevaporizer installed in model 47L are comparable with those obtained with model 30; combustor model 47L without the prevaporizing coils gave slightly higher efficiencies. The prevaporizing system may have affected combustor performance by causing redistribution of air between the primary and secondary zone and by introducing cold surfaces into the reaction zone.

Combustion efficiency with JP-4 fuel. - The combustion efficiency data obtained with JP-4 fuel in model 47L combustor are presented in figure 11 for the test conditions A, B, C, and E. Two curves are shown for model 47L, one for fuel supplied to the prevaporizer at approximately 80° F and the other for fuel supplied at 250° F. The effect of additional fuel preheating is most pronounced at condition E (fig. 11(d)). Since this test condition required fuel-flow rates 69 percent higher than condition A, the condition for which the prevaporizer was designed, the reduced efficiencies with the 80° F fuel are attributed to the insufficient prevaporizing capacity of the coils. In actual aircraft operation fuel would probably be delivered to the combustor at temperatures in excess of 250° F, since the fuel is heated in the engine pumping system, used to cool lubricating oil, and also used to cool a number of aircraft components. The data indicate that under these conditions the prevaporizing coils have an adequate capacity to supply fuel requirements for airflows 69 percent higher than those used in current engines.

Combustion efficiencies obtained with JP-4 fuel in combustor model 30 are included in figure 11. The efficiencies of model 47L are equal to or better than the efficiencies obtained with model 30. While model 30 required three sizes of fuel nozzles to obtain high efficiency over the range of test conditions, model 47 was operated with only one nozzle size. The fuel-nozzle requirements for low-altitude and sea-level operation were not established for either combustor. However, the nozzles used in model 47 combustor would supply the fuel flow required for the reference engine at sea-level take-off conditions with fuel pressures of less than 150 pounds per square inch.

Combustion efficiency with JP-5 fuel. - The current JP-4 jet fuel used in the design calculations and in the experimental research has a relatively high volatility (Reid vapor pressure of 2.9 lb/sq in.), and would require special handling if used for supersonic flight because of the high temperature and subsequent fuel boiling (ref. 9). A lower volatility fuel such as JP-5 (ref. 6) may be preferred for supersonic flight. Since it may be desirable, from a logistic viewpoint, to have a minimum number of

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fuel types, high-altitude subsonic aircraft may be required to operate on the same low-volatility fuel. It has been shown (ref. 10) that decreasing the fuel volatility in a turbojet combustor tends to decrease combustion efficiency at the low-pressure operating conditions that are typical of low-speed high-altitude flight. Prevaporization may be a means of eliminating this penalty.

Combustion efficiency data are presented in figure 12 for JP-5 fuel operation at test conditions A, B, and C. These data were obtained with combustor model 47N prior to the selection of model 47L. Extensive data for JP-5 fuel in model 47L were not obtained because of the accidental plugging of the vaporizer that is discussed later. The efficiency with JP-5 fuel decreased with increasing fuel-air ratios for all conditions; the same trend was obtained with JP-4 fuel at test condition C. At low fuel-air ratios, efficiencies with JP-5 fuel were higher than those with JP-4 at the low-pressure condition. Furthermore, the sharp drop in efficiency with JP-5 fuel is compensated for by increasing the fuel-supply temperature to 250° F (fig. 12). The limited combustion efficiency data obtained with JP-5 fuel in combustor model 47L are presented in figure 13. The efficiency of JP-5 fuel with an 80° F fuel temperature at test condition B is approximately 5 percent lower than that of JP-4 at rated speed, and the efficiency at test condition E is considerably lower. At test condition E two additional curves are presented for inlet fuel temperatures of 250° and 350° F. As would be expected, the combustion efficiency improves with increasing fuel temperatures; although even with an inlet fuel temperature of 350° F, JP-5 fuel efficiency is still 5 percent lower than that of JP-4.

The degree of vaporization attained in the coils is indicated qualitatively by the fuel pressure required to inject fuel at a given flow rate. In figure 14 the fuel pressure at the prevaporizer inlet is shown as a function of the fuel flow at test condition E. These data were obtained with one nozzle configuration L (combustion model 47) with JP-5 and JP-4 fuels. As the fuel flow is increased the fuel pressure increases to a certain point beyond which a further increase in fuel flow results in a decrease in fuel pressure at the prevaporizer inlet. This decrease in fuel pressure at high flow rates is a result of incomplete fuel vaporization and, consequently, decreased volume handling requirements. The effect of fuel volatility on the degree of prevaporization is readily apparent and is directly reflected in injection pressure requirements. The injection pressure required for JP-4 fuel, at an inlet temperature of 80° F, is considerably higher than that required for JP-5, and the injection pressure required for preheated (250° F) JP-5 is higher than that required for JP-5 at 80° F. A larger heat-transfer surface would be required with JP-5 fuel than with JP-4 for the same degree of prevaporization because of the low volatility of JP-5.

[redacted]

No special attempt was made to provide equal fuel distribution to each nozzle or to eliminate slugging which could occur during partial vaporization operation since these problems were not detrimental at the test conditions investigated. The manifold pressure drop supplied uniform fuel distribution to the limited number of fuel injectors, and swirl generators effectively broke up and distributed the partially vaporized fuel.

Prevaporizer system. - No detailed, controlled tests were conducted to determine the extent to which the vaporizer coils might become plugged because of coke and gum deposition. The prevaporizer heat-exchanging coils accumulated approximately 75 hours of running time with JP-4 fuel during this investigation, and 50 hours of running time with JP-4 during the investigation reported in reference 2. No operational difficulties were encountered during this time. During the tests with JP-5 fuel one case of prevaporizer coil plugging was encountered. The plugging occurred when JP-5 fuel was left in the prevaporizing tubes and, a performance check point was obtained with propane fuel admitted directly into the fuel injectors without circulating the fuel through the coils. Because of the low volatility of JP-5 fuel, the coils contained a considerable amount of residual fuel, which cracked and plugged the tubes when heated externally during the propane operation.

Further tests explored the possibility of plugging with JP-5 fuel. Approximately 65 starts and stops were made during a total run time of 20 hours to investigate the effect of leaving hot fuel trapped without purging in the coils. The average fuel-outlet temperature during the runs was between 600° and 700° F. No increase in the prevaporizer pressure drop was noted, as shown in figure 15. The fuel pressure at the prevaporizer inlet is shown as a function of time for JP-5 fuel operation with the prevaporizing coils at test condition B. The fuel-outlet temperature and the progressive number of starts and stops are also indicated in the figure.

Coking of hydrocarbon fuels in electrically heated tubes has been investigated at this laboratory (ref. 11). In tests with fuels having high aromatic and gum contents a rapid buildup of deposit and ultimate plugging of the tube occurred. These fuels had gum contents greater than those permitted under present procurement specifications of MIL-F-5624C. A JP-4 fuel meeting specification of MIL-F-5624C with low gum content was run as long as 70 hours in a heated tube giving a fuel temperature of 1000° F, and showed no evidence of coke formation. The aromatic and gum contents of the JP-5 fuel used in this study and of the production JP-4 fuel tested in reference 11 were very similar. From observations made in this investigation and from results reported in reference 11 it appears that the fuel prevaporizer system described herein will not encounter plugging troubles.

Correlation of combustion efficiency. - Figure 16 presents the correlation of the combustion-efficiency data for the prevaporizing combustor model 47L with the combustion parameter $V_r/P_iT_i$ (ref. 12), where $V_r$ is the combustor reference velocity based on the maximum cross-sectional area (105 sq in.); $P_i$ is the inlet total pressure; and $T_i$ is the inlet-air temperature. The values of combustion efficiency were obtained from the prevaporized JP-4 fuel efficiency curves of figure 10 at a temperature-rise level of 1180° F (required temperature rise for rated speed of the reference turbojet engine). The combustion efficiencies obtained with model 30 (ref. 2) and a commercial vaporizing combustor operated with JP-4 fuel are included in figure 16 for comparison. At a combustor reference velocity of 80 feet per second (test conditions A, B, and C) combustor model 47L operated at approximately the same efficiency as model 30. Combustion efficiencies of the commercial vaporizing combustor are considerably lower than those obtained with the experimental configurations.

Pressure losses. - The combustor pressure losses obtained in combustor model 47L are shown in figure 17. The pressure losses are presented as the ratio of the total-pressure loss to the combustor-inlet total pressure. A 30-percent reduction in pressure loss at a combustor reference velocity of 80 feet per second was achieved by the redesign of the combustor geometry of model 30. Pressure losses in the range of 2 to 4 percent were obtained for model 47L, as compared with losses of 4 to 6 percent in current production model combustors. In this investigation no attempt was made to redesign the combustor housing, and it is possible that a further refinement of the combustor inlet-diffuser section would be reflected in a somewhat lower pressure loss through the combustor.

Combustor-outlet temperature profiles. - The outlet-radial-temperature profile of combustor model 47L and the desired temperature profile are shown in figure 18. The desired temperature profile represents an approximate average of profiles required or desired in a number of current turbojet engines. In figure 18(a) the profile obtained with gaseous propane is presented for test conditions A, B, and C. The average radial temperature profile obtained with gaseous propane follows the desired profile shape closely. With prevaporized liquid fuel (fig. 18(b)) the outlet temperature was somewhat lower at the root position for test conditions B and C; however, at test condition A the profile was comparable to that obtained with gaseous propane operation.

## SUMMARY OF RESULTS

An investigation was conducted to explore means of reducing pressure losses in an experimental fuel-prevaporizing turbojet combustor. The research was directed toward improving the design of the air passages at

the inlet to the combustor. The results for a simulated high-altitude flight in a 5.2-pressure-ratio engine at a flight Mach number of 0.6 are summarized as follows:

1. The combustor (47L) operated with approximately a 30-percent decrease in pressure loss from the previous design (model 30). At a reference velocity of 80 feet per second the combustor pressure losses ranged from 2 to 4 percent as compared with about 4 to 6 percent in production model combustors.

2. Combustion efficiencies were comparable to those obtained in previous experimental designs. Combustion efficiencies of 98, 88, and 81 percent at 56,000, 70,000, and 80,000 feet, respectively, at a temperature rise of 1180° F and a combustor reference velocity of 80 feet per second were obtained with an inlet fuel temperature of 80° F.

3. As the combustor inlet reference velocity was increased from 80 feet per second to 140 feet per second, a marked decrease in combustion efficiency was observed. High efficiencies were again obtained, however, by increasing the inlet fuel temperature to 250° F, a value expected in an actual flight operation.

4. The prevaporizer was operated with three fuels, propane, JP-4, and JP-5. As fuel volatility decreased combustion efficiency also decreased. The combustion efficiency was maintained by supplying additional heat from an outside source to the low-volatility fuel.

5. The outlet-temperature profile was generally satisfactory for the final combustor design.

## CONCLUDING REMARKS

An experimental fuel prevaporizing combustor having pressure losses less than those of current turbojet combustors was developed to provide high combustion efficiencies at high-altitude operating conditions with JP-4 fuel. The use of the less volatile JP-5 fuel resulted in some performance decrease due, at least in part, to limited prevaporizer capacity. This disadvantage could be eliminated by incorporating a larger heat-transfer surface into the prevaporizing coils. From the data obtained, it appears that the combustor could be designed to operate over a wide range of conditions with a fuel similar to JP-5.

Turbojet combustors have been investigated experimentally over increasingly severe operating conditions. Since these inlet conditions approach those that are obtained in high-altitude ram-jet applications, it may be possible to consider turbojet designs for moderately high flight Mach number ram-jet engines where the pressure loss is not too costly.

The use of a vapor fuel instead of liquid-fuel for ram-jet engines would be advantageous in that a wider operating range of fuel-air ratio would be possible, and it would be easier to control the fuel distribution.

The prevaporizing coils were operated for a short endurance run of 20 hours including approximately 65 cycles of start-up and shut-down procedure with JP-5 fuel. No apparent detrimental effects were noted even though hot JP-5 fuel was left in the prevaporizer during shut-down and no provision was made to purge the system. Additional studies, however, would be required to establish fully the reliability of the heat exchanger design.



Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 18, 1956

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TABLE I. - FUEL ANALYSIS

| Fuel properties | JP-4 fuel (MIL-F-5624C) | JP-5 fuel (MIL-F-5624C) |
| --- | --- | --- |
| A.S.T.M. distillation, D86-46, °F | | |
| Initial boiling point | 136 | 360 |
| Percent evaporated | | |
| 5 | 183 | 373 |
| 10 | 200 | 382 |
| 20 | 225 | 399 |
| 30 | 244 | 409 |
| 40 | 263 | 419 |
| 50 | 278 | 429 |
| 60 | 301 | 439 |
| 70 | 321 | 449 |
| 80 | 347 | 459 |
| 90 | 400 | 473 |
| Final boiling point | 498 | 502 |
| Residue, percent | 1.2 | --- |
| Aromatics-silica gel, percent by volume | 10.7 | 13.7 |
| Specific gravity | 0.757 | 0.815 |
| Reid vapor pressure | 2.9 | ---- |
| Accelerated gum, mg/100 ml | --- | 5 |
| Hydrogen-carbon ratio | 0.170 | 0.160 |
| Net heat of combustion, Btu/lb | 18,700 | 18,600 |

[redacted]

TABLE II. - COMBUSTOR TEST DATA

| Run | Combustor-inlet total pressure, in. Hg | Combustor-inlet total temperature, °F | Air-flow rate, lb/sec | Airflow rate per unit area, lb/(sec)(sq ft) | Fuel flow rate, lb/hr | Fuel-air ratio | Mean combustor-outlet temperature, °F | Mean temperature rise through combustor, °F | Combustion efficiency, percent | Inlet fuel temperature, °F | Total-pressure drop through combustor, percent | Combustion parameter, $ft^3/(sec)(lb)(°R)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Model 31K; propane | | | | | | | | | | | | |
| 1 | 15.0 | 270 | 2.64 | 3.62 | 48.6 | 0.0051 | 620 | 350 | 98.6 | 71 | | $172\times10^{-6}$ |
| 2 | 15.0 | 262 | 2.63 | 3.61 | 66.6 | .0071 | 760 | 498 | 97.7 | 78 | | 170 |
| 3 | 15.0 | 254 | 2.61 | 3.58 | 84.2 | .0090 | 860 | 606 | 96.2 | 80 | | 168 |
| 4 | 15.0 | 264 | 2.61 | 3.58 | 100.5 | .0107 | 940 | 676 | 89.4 | 74 | 7.05 | 171 |
| 5 | 15.0 | 248 | 2.61 | 3.58 | 109.5 | .0117 | 990 | 742 | 90.2 | 58 | | 165 |
| 6 | 5.0 | 262 | .533 | .730 | 25.4 | .0132 | 1010 | 748 | 81.3 | 55 | 1.99 | 308 |
| 7 | 5.1 | 262 | .519 | .712 | 29.2 | .0156 | 1065 | 803 | 74.2 | 50 | | 300 |
| 8 | 5.0 | 256 | .518 | .710 | 34.5 | .0185 | 1140 | 884 | 69.6 | 49 | | 298 |
| 9 | 5.0 | 262 | .518 | .710 | 55.0 | .0275 | 1200 | 938 | 48.2 | 49 | | 300 |
| 10 | 8.0 | 268 | .852 | 1.17 | 24.8 | .0081 | 800 | 532 | 97.7 | 52 | 1.87 | 193 |
| 11 | 8.0 | 268 | .833 | 1.14 | 34.6 | .0115 | 945 | 677 | 83.5 | 59 | | 189 |
| 12 | 8.0 | 265 | .833 | 1.14 | 43.7 | .0146 | 1095 | 830 | 82.2 | 55 | | 188 |
| 13 | 8.0 | 266 | .834 | 1.14 | 54.8 | .0182 | 1220 | 954 | 76.8 | 56 | | 188 |
| 14 | 8.0 | 270 | .822 | 1.13 | 81.4 | .0275 | 1390 | 1120 | 61.8 | 54 | | 189 |
| Model 39N; propane | | | | | | | | | | | | |
| 15 | 5.0 | 299 | 0.560 | 0.767 | 20.3 | 0.0099 | 800 | 556 | 81.3 | 70 | | |
| 16 | 5.0 | 256 | .529 | .718 | 26.1 | .0138 | 1050 | 794 | 83.8 | 63 | | |
| 17 | 5.0 | 270 | .521 | .713 | 31.5 | .0168 | 1195 | 925 | 80.9 | 59 | | |
| 18 | 5.0 | 262 | .521 | .713 | 36.8 | .0196 | 1300 | 1038 | 78.2 | 56 | | |
| 19 | 5.0 | 268 | .521 | .713 | 48.0 | .0256 | 1380 | 1112 | 65.8 | 52 | | |
| Model 45K; propane | | | | | | | | | | | | |
| 20 | 5.0 | 260 | 0.520 | 0.713 | 20.9 | 0.0112 | 820 | 560 | 65.0 | 79 | | $300\times10^{-6}$ |
| 21 | 5.0 | 272 | .520 | .713 | 25.2 | .0134 | 970 | 698 | 68.5 | 79 | | 306 |
| 22 | 5.0 | 270 | .520 | .713 | 36.3 | .0195 | 1220 | 950 | 67.0 | 79 | | 305 |
| 23 | 5.0 | 270 | .520 | .713 | 41.4 | .0221 | 1350 | 1080 | 66.0 | 80 | | 305 |
| Model 45L; propane | | | | | | | | | | | | |
| 24 | 5.0 | 266 | 0.521 | 0.714 | 14.7 | 0.0079 | 785 | 519 | 85.0 | 78 | | $302\times10^{-6}$ |
| 25 | 5.0 | 271 | .515 | .705 | 20.7 | .0112 | 990 | 719 | 84.7 | 77 | | 306 |
| 26 | 5.0 | 267 | .521 | .714 | 25.4 | .0135 | 1140 | 873 | 89.7 | 73 | | 303 |
| 27 | 5.0 | 264 | .515 | .705 | 30.5 | .0169 | 1270 | 1006 | 82.8 | 73 | | 301 |
| 28 | 5.0 | 266 | .521 | .714 | 35.5 | .0190 | 1400 | 1134 | 82.3 | 74 | | 302 |
| 29 | 5.0 | 263 | .521 | .714 | 40.7 | .0216 | 1520 | 1257 | 80.7 | 73 | | 301 |
| 30 | 8.0 | 264 | .840 | 1.15 | 25.3 | .0089 | 875 | 611 | 94.5 | 75 | | 190 |
| 31 | 8.0 | 265 | .840 | 1.15 | 35.6 | .0118 | 1070 | 805 | 90.2 | 74 | | 190 |
| 32 | 8.0 | 267 | .840 | 1.15 | 45.5 | .0150 | 1250 | 983 | 87.4 | 76 | | 191 |
| 33 | 8.0 | 263 | .840 | 1.15 | 57.0 | .0189 | 1420 | 1157 | 84.5 | 75 | | 189 |
| 34 | 8.0 | 264 | .840 | 1.15 | 67.7 | .0224 | 1570 | 1306 | 82.0 | 76 | | 190 |
| Model 45Q; propane | | | | | | | | | | | | |
| 35 | 5.0 | 270 | 0.514 | 0.705 | 36.8 | 0.0197 | 1400 | 1130 | 79.4 | 74 | | $305\times10^{-6}$ |
| 36 | 5.0 | 262 | .518 | .710 | 36.8 | .01955 | 1400 | 1130 | 80.5 | 73 | | 300 |
| 37 | 5.0 | 264 | .516 | .705 | 41.8 | .0225 | 1465 | 1195 | 74.3 | 74 | | 301 |
| 38 | 5.0 | 264 | .520 | .713 | 21.8 | .0117 | 925 | 661 | 74.1 | 81 | | 301 |
| 39 | 5.0 | 265 | .520 | .713 | 25.3 | .0135 | 1055 | 790 | 77.0 | 82 | | 302 |
| 40 | 5.0 | 262 | .520 | .713 | 35.7 | .0192 | 1340 | 1078 | 76.3 | 83 | | 301 |
| 41 | 5.0 | 265 | .520 | .713 | 41.5 | .0222 | 1345 | 1080 | 66.2 | 84 | | 302 |
| Model 47L; propane - no prevaporizer | | | | | | | | | | | | |
| 42 | 5.0 | 273 | 0.530 | 0.726 | 20.6 | 0.0108 | 1010 | 737 | 89.0 | 84 | 2.5 | $308\times10^{-6}$ |
| 43 | 5.0 | 270 | .527 | .722 | 27.5 | .0133 | 1160 | 890 | 89.2 | 82 | | 306 |
| 44 | 5.0 | 271 | .530 | .726 | 30.3 | .0160 | 1310 | 1039 | 88.2 | 82 | | 306 |
| 45 | 5.0 | 272 | .527 | .722 | 32.3 | .0187 | 1440 | 1168 | 86.2 | 81 | 3.0 | 306 |
| 46 | 5.0 | 272 | .527 | .722 | 34.0 | .0211 | 1550 | 1278 | 84.6 | 82 | | 306 |
| 45 | 5.0 | 280 | .525 | .719 | 19.4 | .0093 | 880 | 600 | 84.0 | 92 | | 309 |
| 48 | 5.0 | 272 | .521 | .714 | 22.7 | .0112 | 1010 | 738 | 88.5 | 90 | | 305 |
| 49 | 5.0 | 272 | .521 | .714 | 32.1 | .0188 | 1430 | 1158 | 84.8 | 90 | | 305 |
| 50 | 8.0 | 270 | .822 | 1.13 | 25.3 | .0086 | 930 | 660 | 100.0 | 91 | 2.7 | 188 |
| 51 | 8.0 | 269 | .816 | 1.12 | 30.3 | .0103 | 1025 | 756 | 95.6 | 93 | | 187 |
| 52 | 8.0 | 269 | .817 | 1.12 | 35.3 | .0120 | 1140 | 871 | 96.5 | 94 | | 187 |
| 53 | 8.0 | 269 | .816 | 1.12 | 40.6 | .0138 | 1250 | 981 | 99.2 | 95 | | 187 |
| 54 | 8.0 | 270 | .816 | 1.12 | 45.2 | .0154 | 1345 | 1075 | 94.8 | 97 | | 188 |
| 55 | 8.0 | 271 | .815 | 1.12 | 50.4 | .0172 | 1435 | 1164 | 92.7 | 98 | | 188 |
| 56 | 8.0 | 271 | .813 | 1.115 | 60.3 | .0206 | 1580 | 1309 | 88.5 | 99 | | 187 |
| 57 | 15.0 | 249 | 1.536 | 2.10 | 59.2 | .0106 | 1070 | 821 | 102.1 | 98 | | 96 |
| 58 | 15.0 | 268 | 1.546 | 2.12 | 67.0 | .0120 | 1180 | 912 | 100.3 | 98 | | 100 |
| 59 | 15.0 | 268 | 1.552 | 2.13 | 74.2 | .0133 | 1270 | 1002 | 100.6 | 98 | | 100 |
| 60 | 15.0 | 267 | 1.553 | 2.13 | 82.6 | .0148 | 1350 | 1083 | 99.3 | 97 | | 100 |
| 61 | 15.0 | 268 | 1.550 | 2.12 | 92.1 | .0165 | 1450 | 1182 | 97.8 | 97 | 3.6 | 100 |
| 62 | 15.0 | 268 | 1.550 | 2.12 | 102.1 | .0183 | 1550 | 1282 | 97.0 | 97 | | 100 |
| 63 | 15.0 | 266 | 2.638 | 3.61 | 76.9 | .0081 | 905 | 639 | 101.5 | 76 | | 171 |
| 64 | 14.9 | 270 | 2.630 | 3.60 | 95.0 | .0100 | 1040 | 770 | 101.0 | 76 | | 172 |
| 65 | 15.0 | 263 | 2.645 | 3.63 | 111.1 | .0117 | 1145 | 882 | 100.7 | 77 | | 170 |
| 66 | 15.0 | 266 | 2.641 | 3.62 | 132.0 | .0139 | 1280 | 1014 | 97.8 | 79 | | 171 |
| 67 | 15.1 | 272 | 2.638 | 3.61 | 153.8 | .0162 | 1410 | 1138 | 96.0 | 80 | | 172 |
| 68 | 15.1 | 262 | 2.675 | 3.67 | 171.2 | .0179 | 1475 | 1213 | 93.5 | 84 | 13.7 | 170 |
| Model 47L; propane - prevaporizer | | | | | | | | | | | | |
| 69 | 5.0 | 268 | 0.525 | 0.720 | 21.3 | 0.0113 | 970 | 702 | 81.8 | 96 | 1.8 | $302\times10^{-6}$ |
| 70 | 5.0 | 258 | .525 | .720 | 24.8 | .0131 | 1075 | 817 | 82.8 | 95 | | 298 |
| 71 | 5.0 | 267 | .525 | .720 | 27.4 | .0145 | 1155 | 888 | 81.8 | 99 | | 302 |
| 72 | 5.0 | 262 | .525 | .720 | 30.5 | .0162 | 1240 | 978 | 80.8 | 92 | | 300 |
| 73 | 5.0 | 267 | .525 | .720 | 33.0 | .0175 | 1300 | 1033 | 80.6 | 87 | | 302 |
| 74 | 5.0 | 265 | .525 | .720 | 38.5 | .0204 | 1450 | 1185 | 80.5 | 82 | 3.6 | 301 |
| 75 | 5.0 | 267 | .525 | .720 | 36.5 | .0193 | 1400 | 1133 | 80.7 | 80 | | 302 |
| 76 | 8.0 | 269 | .835 | 1.14 | 25.8 | .0086 | 895 | 626 | 93.5 | 79 | | 191 |
| 77 | 8.0 | 278 | .835 | 1.14 | 29.7 | .0099 | 985 | 707 | 93.3 | 77 | 3.5 | 193 |
| 78 | 8.0 | 271 | .835 | 1.14 | 32.5 | .0118 | 1100 | 829 | 93.5 | 76 | | 191 |
| 79 | 8.0 | 265 | .835 | 1.14 | 42.6 | .0142 | 1220 | 955 | 91.3 | 74 | | 190 |
| 80 | 8.0 | 258 | .835 | 1.14 | 48.9 | .0163 | 1325 | 1067 | 90.3 | 74 | | 187 |
| 81 | 8.0 | 258 | .835 | 1.14 | 55.2 | .0184 | 1420 | 1162 | 88.5 | 74 | 3.6 | 187 |
| 82 | 15.0 | 262 | 1.56 | 2.14 | 45.3 | .0081 | 880 | 618 | 98.4 | 77 | | 99 |
| 83 | 15.0 | 271 | 1.56 | 2.14 | 59.1 | .0105 | 1040 | 769 | 98.3 | 86 | 3.5 | 102 |
| 84 | 15.1 | 262 | 1.56 | 2.14 | 68.4 | .0122 | 1140 | 878 | 96.0 | 74 | | 99 |
| 85 | 15.0 | 268 | 1.56 | 2.14 | 77.0 | .0137 | 1235 | 967 | 94.7 | 71 | | 102 |
| 86 | 15.0 | 264 | 1.56 | 2.14 | 83.1 | .0148 | 1300 | 1036 | 98.0 | 70 | | 101 |
| 87 | 15.0 | 260 | 1.56 | 2.14 | 93.8 | .0167 | 1475 | 1215 | 100.0 | 68 | 4.0 | 99 |
| 88 | 14.9 | 268 | 2.63 | 3.60 | 76.8 | .0081 | 870 | 602 | 95.5 | 72 | | 172 |
| 89 | 15.1 | 253 | 2.67 | 3.66 | 96.1 | .0100 | 1000 | 747 | 97.9 | 67 | | 168 |
| 90 | 15.2 | 261 | 2.67 | 3.66 | 106.0 | .0111 | 1080 | 819 | 97.9 | 64 | 10.3 | 171 |
| 91 | 15.0 | 259 | 2.67 | 3.66 | 127.5 | .0133 | 1210 | 951 | 96.2 | 64 | | 169 |
| 92 | 15.1 | 256 | 2.67 | 3.66 | 149.0 | .0155 | 1320 | 1064 | 94.7 | 64 | | 168 |

[redacted]

4100

4180

CH-3 back



TABLE II. - Concluded. COMBUSTOR TEST DATA

| Run | Combustor-inlet total pressure, in. Hg | Combustor-inlet total temperature, °F | Air-flow rate, lb/sec | Airflow rate per unit area, lb/(sec)(sq ft) | Fuel flow rate, lb/hr | Fuel-air ratio | Mean combustor-outlet temperature, °F | Mean temperature rise through combustor, °F | Combustion efficiency, percent | Inlet fuel temperature, °F | Fuel temperature after prevaporizing, °F | Fuel manifold pressure, lb/(sq in.) gage | Total-pressure drop through combustor, percent | Combustion parameter, ft³/(sec)(lb)(°R) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Model 47L; JP-4 | | | | | | | |
| 93 | 5.0 | 268 | 0.521 | 0.714 | 20.0 | 0.0109 | 890 | 622 | 81.8 | 84 | 610 | 4±0 | | 300x10⁻⁶ |
| 94 | 5.0 | 267 | .526 | .721 | 29.3 | .0129 | 1040 | 773 | 84.7 | 88 | 620 | 6±0 | 3.2 | 303 |
| 95 | 5.0 | 268 | .526 | .721 | 30.0 | .0158 | 1180 | 912 | 85.5 | 91 | 690 | 12±1 | | 303 |
| 96 | 5.1 | 273 | .526 | .721 | 32.2 | .0170 | 1270 | 997 | 84.4 | 96 | 640 | 16±1 | | 304 |
| 97 | 5.0 | 266 | .526 | .721 | 36.0 | .0190 | 1340 | 1074 | 82.1 | 97 | 620 | 18±5 | | 302 |
| 98 | 5.3 | 270 | .526 | .721 | 40.0 | .0211 | 1430 | 1160 | 80.8 | 99 | 600 | 20±5 | | 303 |
| 99 | 5.0 | 270 | .526 | .721 | 39.9 | .0210 | 1420 | 1150 | 80.8 | 99 | 580 | 20±5 | | 303 |
| 100 | 5.0 | 260 | .526 | .721 | 43.7 | .0231 | 1480 | 1220 | 78.1 | 100 | 460 | 19±0 | 3.8 | 300 |
| 101 | 8.0 | 272 | .835 | 1.145 | 26.0 | .0087 | 870 | 598 | 94.9 | 100 | 590 | 9±1 | | 190 |
| 102 | 8.0 | 260 | .835 | 1.146 | 32.0 | .0106 | 970 | 710 | 92.8 | 99 | 590 | 12±3 | 3.6 | 187 |
| 103 | 8.1 | 260 | .838 | 1.146 | 36.0 | .0120 | 1040 | 780 | 91.2 | 99 | 600 | 15±5 | | 187 |
| 104 | 7.9 | 270 | .836 | 1.146 | 41.6 | .0138 | 1160 | 890 | 91.0 | 100 | 590 | 22±7 | | 190 |
| 105 | 8.0 | 270 | .836 | 1.146 | 45.0 | .0150 | 1230 | 960 | 91.4 | 100 | 590 | 27±7 | | 190 |
| 106 | 8.0 | 270 | .836 | 1.146 | 50.1 | .0166 | 1290 | 1020 | 88.6 | 100 | 590 | 30±10 | | 190 |
| 107 | 8.2 | 261 | .836 | 1.146 | 53.0 | .0176 | 1350 | 1089 | 87.0 | 101 | 590 | 20±10 | | 187 |
| 108 | 8.0 | 260 | .836 | 1.146 | 60.2 | .0200 | 1460 | 1200 | 88.0 | 101 | 550 | 37±10 | | 187 |
| 109 | 8.0 | 260 | .836 | 1.146 | 67.2 | .0224 | 1550 | 1290 | 85.7 | 103 | 500 | 40±2 | 4.0 | 187 |
| 110 | 8.0 | 270 | .832 | 1.140 | 34.8 | .0116 | 1020 | 750 | 90.6 | 252 | 660 | 18±0 | | 190 |
| 111 | 8.0 | 265 | .832 | 1.140 | 41.6 | .0139 | 1150 | 885 | 92.2 | 250 | 670 | 25±1 | | 189 |
| 112 | 8.0 | 268 | .832 | 1.140 | 56.4 | .0187 | 1415 | 1147 | 91.5 | 237 | 670 | 40±15 | | 189 |
| 113 | 5.0 | 272 | .524 | .718 | 32.0 | .0170 | 1270 | 998 | 85.0 | 212 | 660 | 15±1 | 3.0 | 306 |
| 114 | 5.0 | 260 | .524 | .718 | 36.0 | .0190 | 1340 | 1080 | 82.3 | 230 | 640 | 21±1 | | 303 |
| 115 | 5.0 | 268 | .524 | .718 | 42.0 | .0222 | 1480 | 1212 | 81.7 | 237 | 600 | 23±2 | | 305 |
| 116 | 5.0 | 262 | .524 | .718 | 44.4 | .0234 | 1930 | 1258 | 80.8 | 237 | 560 | 25±2 | | 303 |
| 117 | 15.0 | 269 | 1.57 | 2.15 | 48.2 | .0085 | 845 | 576 | 92.7 | 94 | 490 | 17±7 | | 102 |
| 118 | 15.0 | 266 | 1.57 | 2.15 | 56.2 | .0100 | 965 | 699 | 97.3 | 93 | 500 | 30±7 | | 101 |
| 119 | 15.0 | 273 | 1.56 | 2.14 | 64.5 | .0115 | 1080 | 807 | 98.5 | 94 | 490 | 40±15 | 3.0 | 103 |
| 120 | 15.0 | 273 | 1.56 | 2.14 | 76.5 | .0136 | 1210 | 937 | 98.1 | 94 | 480 | 41±1 | | 103 |
| 121 | 15.0 | 268 | 1.56 | 2.14 | 83.4 | .0148 | 1280 | 1012 | 97.8 | 94 | 460 | 43±2 | | 102 |
| 122 | 15.0 | 263 | 1.56 | 2.14 | 97.0 | .0173 | 1430 | 1167 | 97.8 | 94 | 440 | 52±1 | 4.5 | 102 |
| 123 | 15.0 | 260 | 1.57 | 2.15 | 110.5 | .0196 | 1520 | 1260 | 94.6 | 94 | 420 | 55±1 | | 100 |
| 124 | 15.0 | 256 | 1.56 | 2.14 | 49.0 | .0087 | 890 | 634 | 100 | 249 | 560 | 30±5 | | 99 |
| 125 | 15.0 | 268 | 1.56 | 2.14 | 82.0 | .0146 | 1260 | 992 | 97.2 | 232 | 560 | 50±10 | | 102 |
| 126 | 15.0 | 260 | 1.56 | 2.14 | 95.0 | .0169 | 1410 | 1150 | 98.2 | 248 | 530 | 67±1 | | 100 |
| 127 | 15.0 | 261 | 1.56 | 2.14 | 109.5 | .0195 | 1530 | 1269 | 95.6 | 246 | 550 | 78±1 | 4.2 | 100 |
| 128 | 15.0 | 238 | 2.64 | 3.62 | 73.8 | .0077 | 770 | 532 | 94.5 | 100 | 320 | 23±0 | | 165 |
| 129 | 15.1 | 268 | 2.64 | 3.62 | 99.2 | .0105 | 965 | 697 | 93.0 | 100 | 320 | 34±0 | | 172 |
| 130 | 15.1 | 258 | 2.64 | 3.62 | 114.0 | .0120 | 1055 | 797 | 93.5 | 96 | 330 | 37±0 | | 169 |
| 131 | 15.0 | 261 | 2.64 | 3.62 | 131.0 | .0138 | 1145 | 884 | 90.7 | 93 | 330 | 39±0 | | 170 |
| 132 | 15.0 | 263 | 2.64 | 3.62 | 130.0 | .0137 | 1150 | 887 | 97.1 | 90 | 330 | 39±0 | | 170 |
| 133 | 15.0 | 266 | 2.64 | 3.62 | 160.0 | .0168 | 1300 | 1034 | 88.4 | 88 | 320 | 36±0 | | 171 |
| 134 | 15.2 | 268 | 2.64 | 3.62 | 180.5 | .0190 | 1365 | 1097 | 83.8 | 87 | 310 | 35±0 | | 172 |
| 135 | 15.0 | 268 | 2.64 | 3.62 | 196.0 | .0205 | 1400 | 1132 | 80.8 | 85 | 310 | 30±0 | | 172 |
| 136 | 15.1 | 272 | 2.64 | 3.62 | 73.0 | .0077 | 795 | 523 | 99.3 | 268 | 400 | 36±0 | | 171 |
| 137 | 15.0 | 272 | 2.64 | 3.62 | 94.8 | .0100 | 970 | 698 | 97.2 | 272 | 410 | 50±0 | | 172 |
| 138 | 15.0 | 271 | 2.64 | 3.62 | 127.3 | .0134 | 1180 | 909 | 97.0 | 251 | 400 | 63±0 | | 172 |
| 139 | 15.0 | 272 | 2.64 | 3.62 | 147.0 | .0155 | 1325 | 1053 | 97.8 | 250 | 390 | 72±0 | | 172 |
| 140 | 15.1 | 270 | 2.64 | 3.62 | 156.0 | .0165 | 1380 | 1110 | 97.8 | 242 | 390 | 75±0 | | 171 |
| 141 | 15.0 | 260 | 2.64 | 2.62 | 164.0 | .0173 | 1420 | 1160 | 97.4 | 240 | 380 | 80±0 | | 170 |
| | | | | | | | Model 47N; JP-5 | | | | | | | |
| 142 | 15.1 | 254 | 1.55 | 2.12 | 50.5 | 0.0091 | 900 | 646 | 99.0 | 84 | 510 | 15±5 | | 97x10⁻⁶ |
| 143 | 15.0 | 266 | 1.55 | 2.12 | 59.0 | .0106 | 1020 | 754 | 100.0 | 88 | 510 | 15±9 | | 99 |
| 144 | 15.0 | 270 | 1.55 | 2.12 | 68.2 | .0122 | 1130 | 860 | 99.3 | 87 | 510 | 18±2 | | 101 |
| 145 | 15.0 | 272 | 1.56 | 2.14 | 80.5 | .0143 | 1245 | 973 | 97.5 | 87 | 490 | 21±1 | | 102 |
| 146 | 15.0 | 272 | 1.56 | 2.14 | 91.5 | .0163 | 1310 | 1038 | 92.0 | 85 | 440 | 22±0 | | 102 |
| 147 | 15.0 | 279 | 1.56 | 2.14 | 109.0 | .0194 | 1400 | 1126 | 85.2 | 83 | 400 | 11±0 | 3.9 | 102 |
| 148 | 15.2 | 273 | 1.56 | 2.14 | 118.3 | .0210 | 1476 | 1197 | 89.2 | 82 | 390 | 6.5±0 | | 100 |
| 149 | 8.0 | 292 | .875 | 1.20 | 28.0 | .0089 | 870 | 578 | 90.0 | 85 | 600 | 5±0 | | 205 |
| 150 | 8.0 | 289 | .833 | 1.14 | 38.8 | .0129 | 1090 | 806 | 88.7 | 89 | 630 | 12±5 | | 193 |
| 151 | 8.0 | 268 | .847 | 1.16 | 40.6 | .0134 | 1150 | 882 | 97.8 | 94 | 610 | 13±4 | | 194 |
| 152 | 8.1 | 272 | .838 | 1.15 | 49.3 | .0164 | 1275 | 1003 | 88.7 | 96 | 600 | 16±1 | | 190 |
| 153 | 8.1 | 264 | .839 | 1.15 | 61.0 | .0202 | 1430 | 1166 | 84.8 | 98 | 500 | 17±3 | | 188 |
| 154 | 5.0 | 256 | .532 | .728 | 23.9 | .0125 | 1040 | 784 | 88.5 | 101 | 650 | 4±1/2 | 3.0 | 298 |
| 155 | 5.0 | 263 | .532 | .728 | 31.4 | .0164 | 1210 | 947 | 83.0 | 98 | 580 | 6±2 | | 301 |
| 156 | 5.0 | 266 | .523 | .716 | 37.2 | .0197 | 1310 | 1044 | 77.5 | 97 | 540 | 6±1 | | 302 |
| 157 | 5.0 | 262 | .523 | .715 | 45.0 | .0238 | 1370 | 1108 | 68.8 | 100 | 430 | 8±1 | | 301 |
| 158 | 5.2 | 260 | .528 | .724 | 42.1 | .0222 | 1455 | 1195 | 77.5 | 292 | 630 | 17±5 | | 289 |
| 159 | 5.0 | 260 | .528 | .724 | 42.0 | .0221 | 1440 | 1180 | 76.9 | 290 | 625 | 17±5 | | 300 |
| | | | | | | | Model 47L; JP 5 | | | | | | | |
| 160 | 15.1 | 264 | 2.60 | 3.65 | 97.0 | 0.0101 | 880 | 616 | 84.3 | 87 | 370 | 11±0 | | 171x10⁻⁶ |
| 161 | 15.2 | 260 | 2.65 | 3.63 | 115.0 | .0121 | 1045 | 785 | 91.4 | 89 | 380 | 19±0 | 10.5 | 170 |
| 162 | 15.0 | 258 | 2.65 | 3.63 | 133.6 | .0140 | 1140 | 882 | 89.5 | 89 | 380 | 12.5±0 | | 170 |
| 163 | 15.0 | 268 | 2.65 | 3.63 | 161.2 | .0169 | 1240 | 972 | 83.0 | 87 | 360 | 8.5±0 | | 172 |
| 164 | 15.0 | 275 | 2.65 | 3.63 | 193.5 | .0206 | 1375 | 1100 | 78.4 | 86 | 370 | 5.5±0 | | 174 |
| 165 | 15.0 | 266 | 2.69 | 3.62 | 95.8 | .0101 | 920 | 654 | 91.4 | 285 | 440 | 24±0 | | 171 |
| 166 | 15.1 | 268 | 2.66 | 3.65 | 108.8 | .0113 | 1045 | 777 | 96.7 | 252 | 440 | 26±0 | | 172 |
| 167 | 15.0 | 268 | 2.66 | 3.65 | 130.8 | .0136 | 1170 | 902 | 95.5 | 258 | 440 | 27±0 | | 172 |
| 168 | 15.2 | 268 | 2.66 | 3.65 | 149.0 | .0155 | 1290 | 1022 | 95.7 | 270 | 440 | 28.5±0 | | 170 |
| 169 | 15.0 | 268 | 2.66 | 3.65 | 185.0 | .0192 | 1370 | 1102 | 89.9 | 252 | 400 | 19±0 | | 172 |
| 170 | 15.1 | 269 | 2.66 | 3.65 | 179.0 | .0185 | 1415 | 1146 | 91.5 | 346 | 445 | 37±0 | | 171 |
| 171 | 8.0 | 267 | .835 | 1.145 | 28.2 | .0094 | 880 | 613 | 90.5 | 84 | 600 | 5±1 | | 191 |
| 172 | 8.1 | 272 | .835 | 1.145 | 39.6 | .0132 | 1100 | 828 | 89.4 | 85 | 620 | 12±3 | | 190 |
| 173 | 8.0 | 264 | .840 | 1.15 | 44.8 | .0147 | 1150 | 886 | 86.5 | 85 | 610 | 13±5 | | 188 |
| 174 | 8.0 | 267 | .833 | 1.14 | 49.2 | .0164 | 1270 | 1003 | 87.8 | 86 | 600 | 16±1 | | 191 |
| 175 | 8.1 | 272 | .825 | 1.13 | 61.7 | .0208 | 1450 | 1178 | 83.7 | 86 | 520 | 17±3 | | 188 |

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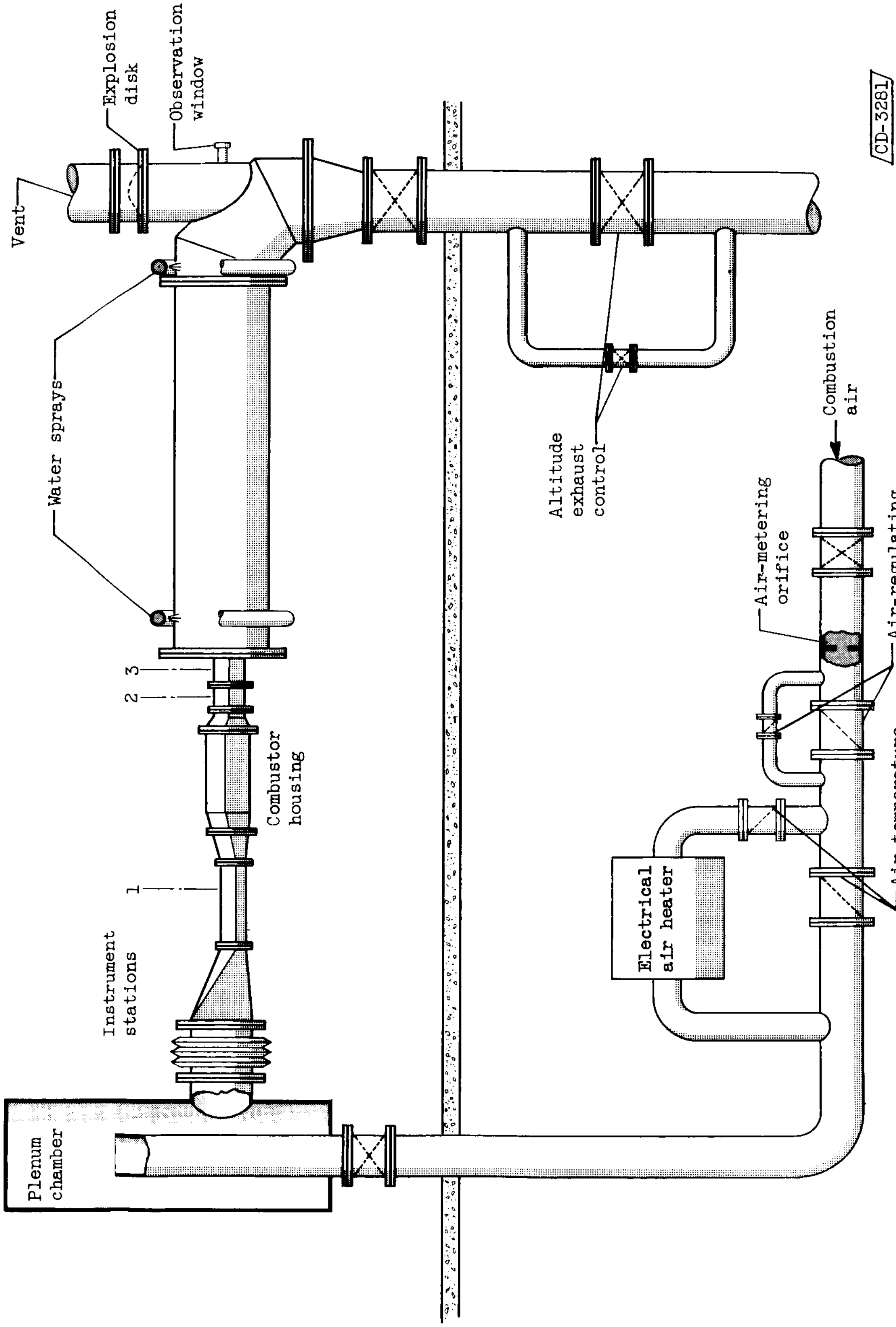


Figure 1. - Installation of one-quarter sector of 25.5-inch-diameter annular combustor.

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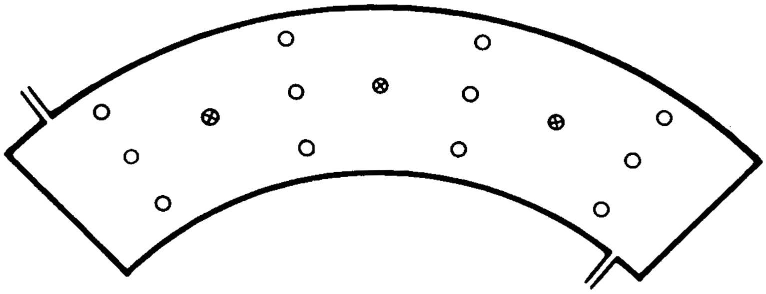
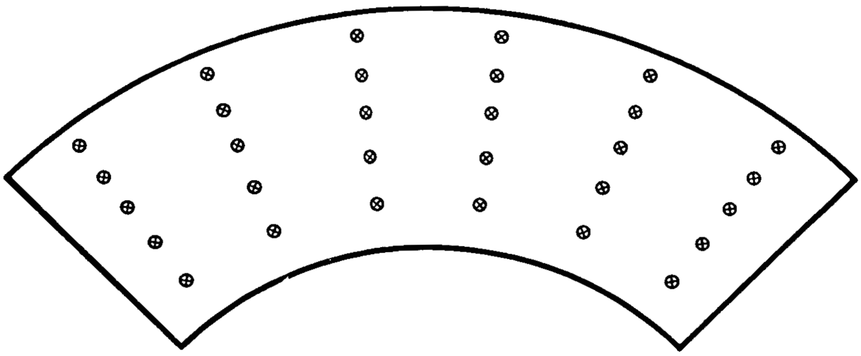


(a) Inlet thermocouples (iron-constantan) and total-pressure probes in plane at station 1.

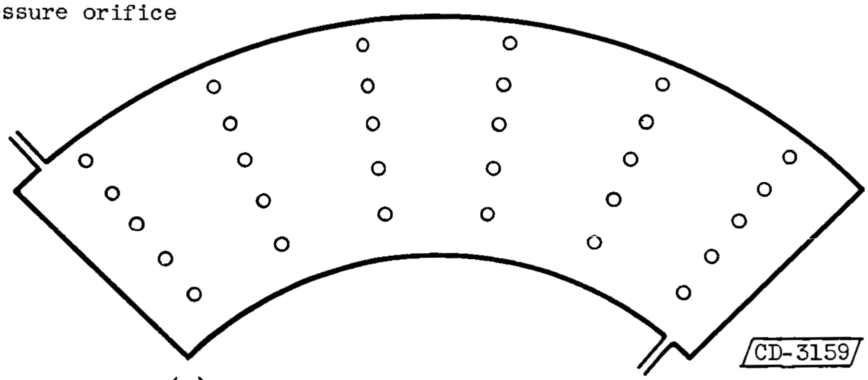


(b) Outlet thermocouples (chromel-alumel) in plane at station 2.

⊗ Thermocouple

○ Total-pressure probe

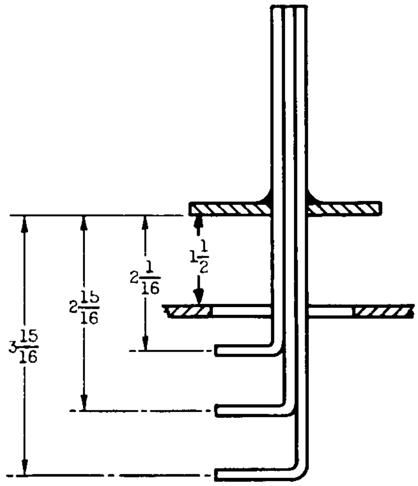
Static-pressure orifice



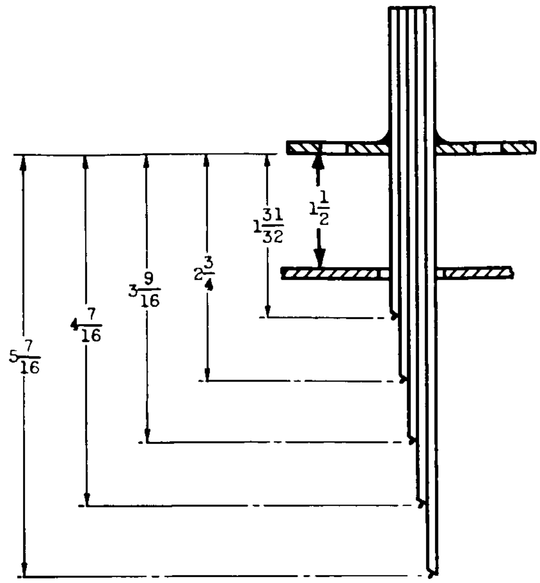

(c) Outlet total-pressure probes in plane at station 3.

Figure 2. - Experimental combustor instrumentation.

[redacted]




(d) Inlet total-pressure rake.




(e) Outlet thermocouple rake.

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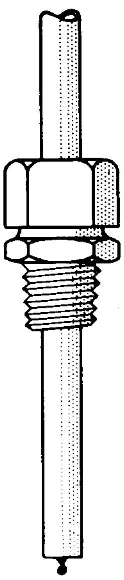
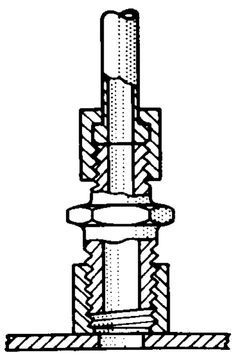
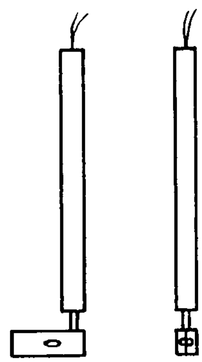


(f) Inlet thermocouple.



(g) Static-pressure orifice.



(h) Wedge stream-static probe.

CD-2846

Figure 2. - Concluded. Experimental combustor instrumentation.

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CD-3779

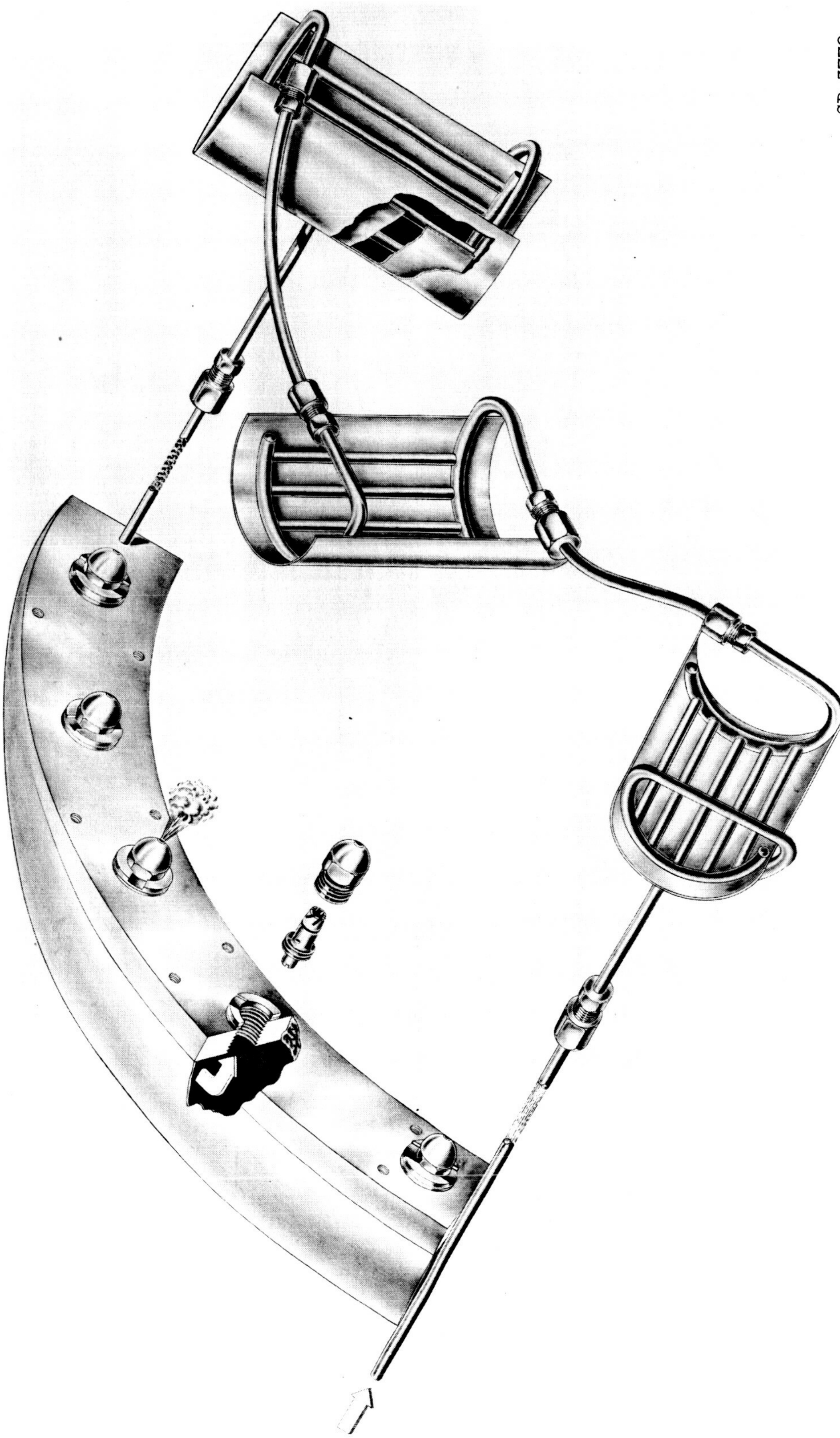

Figure 3. - Fuel-prevaporizing system in combustor model 47 (similar to model 30, ref. 2).

[redacted]

[redacted]

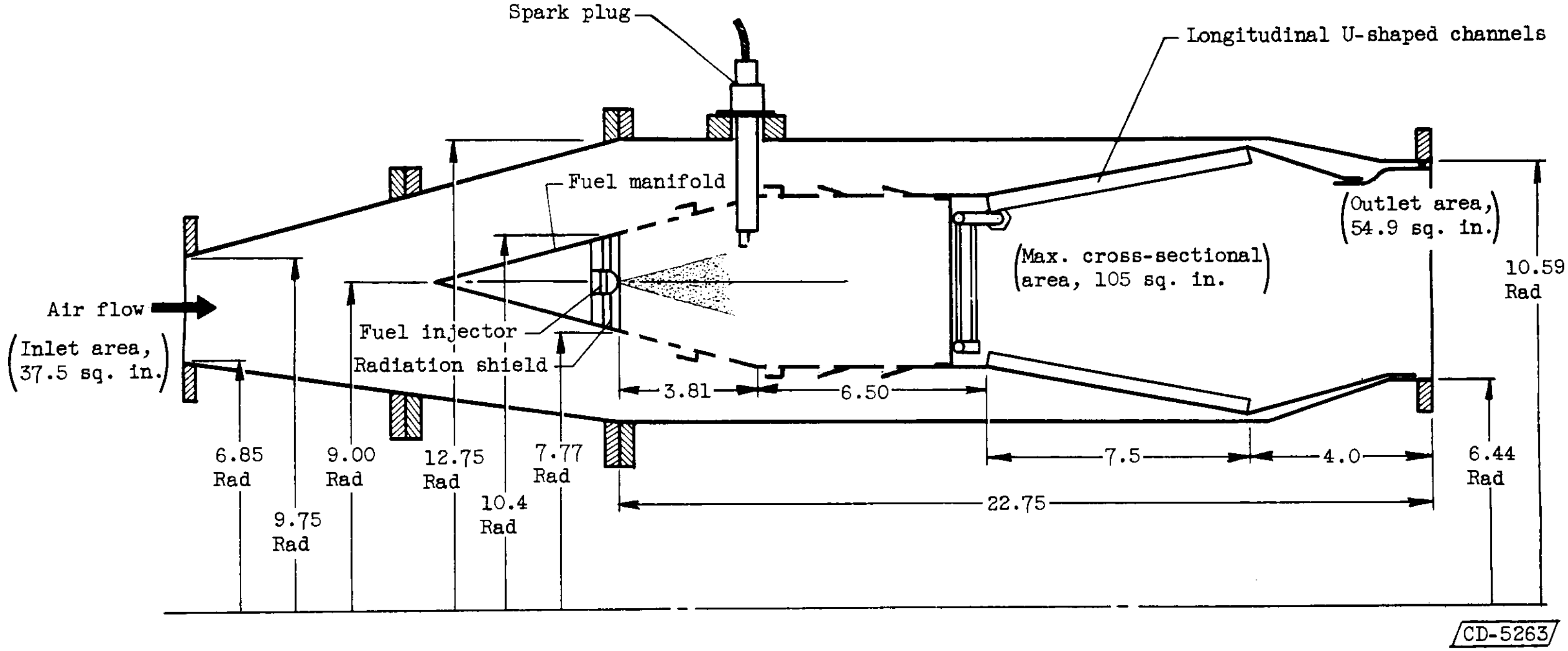


Figure 4. - Longitudinal cross-sectional view of combustor and housing. (Dimensions are in inches.)

[redacted]

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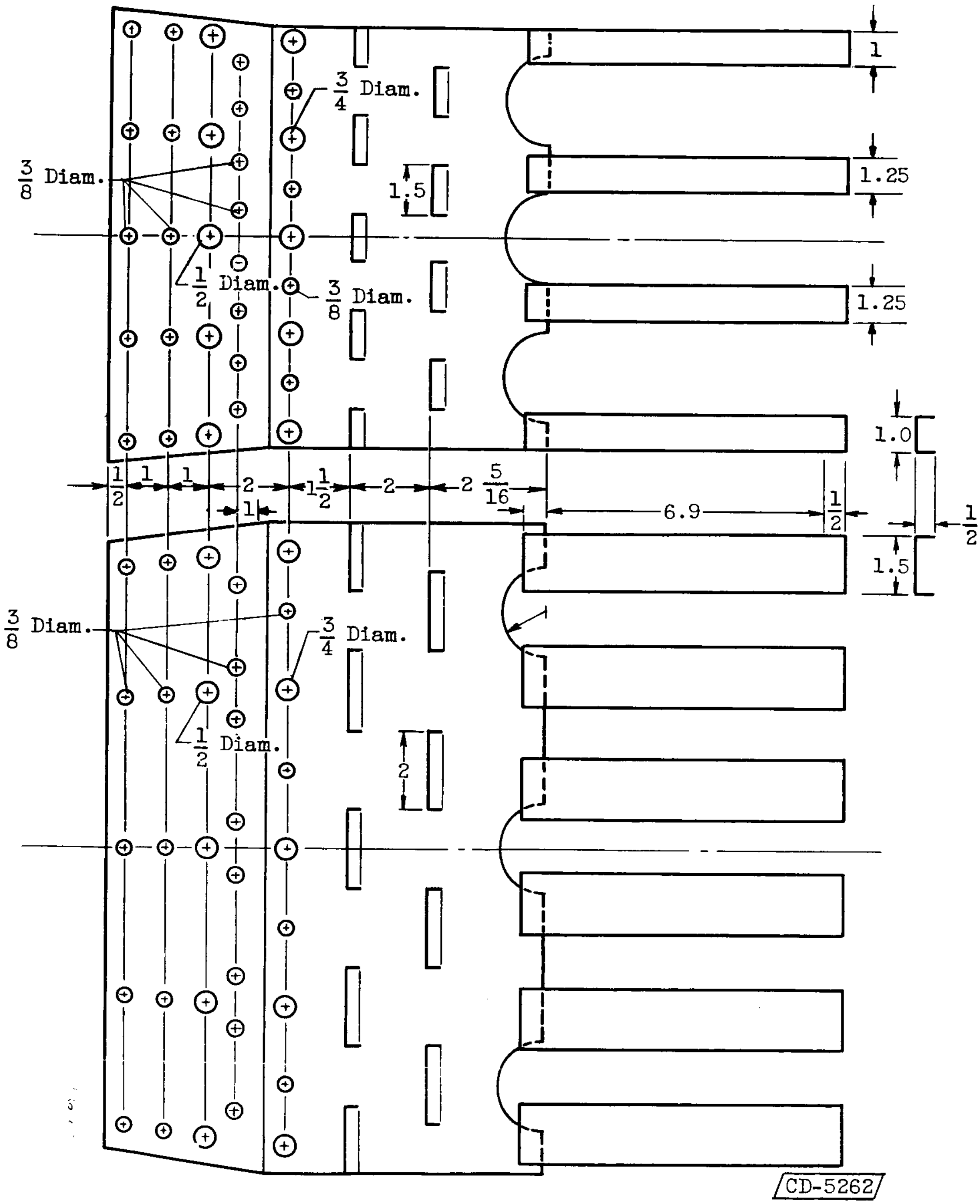
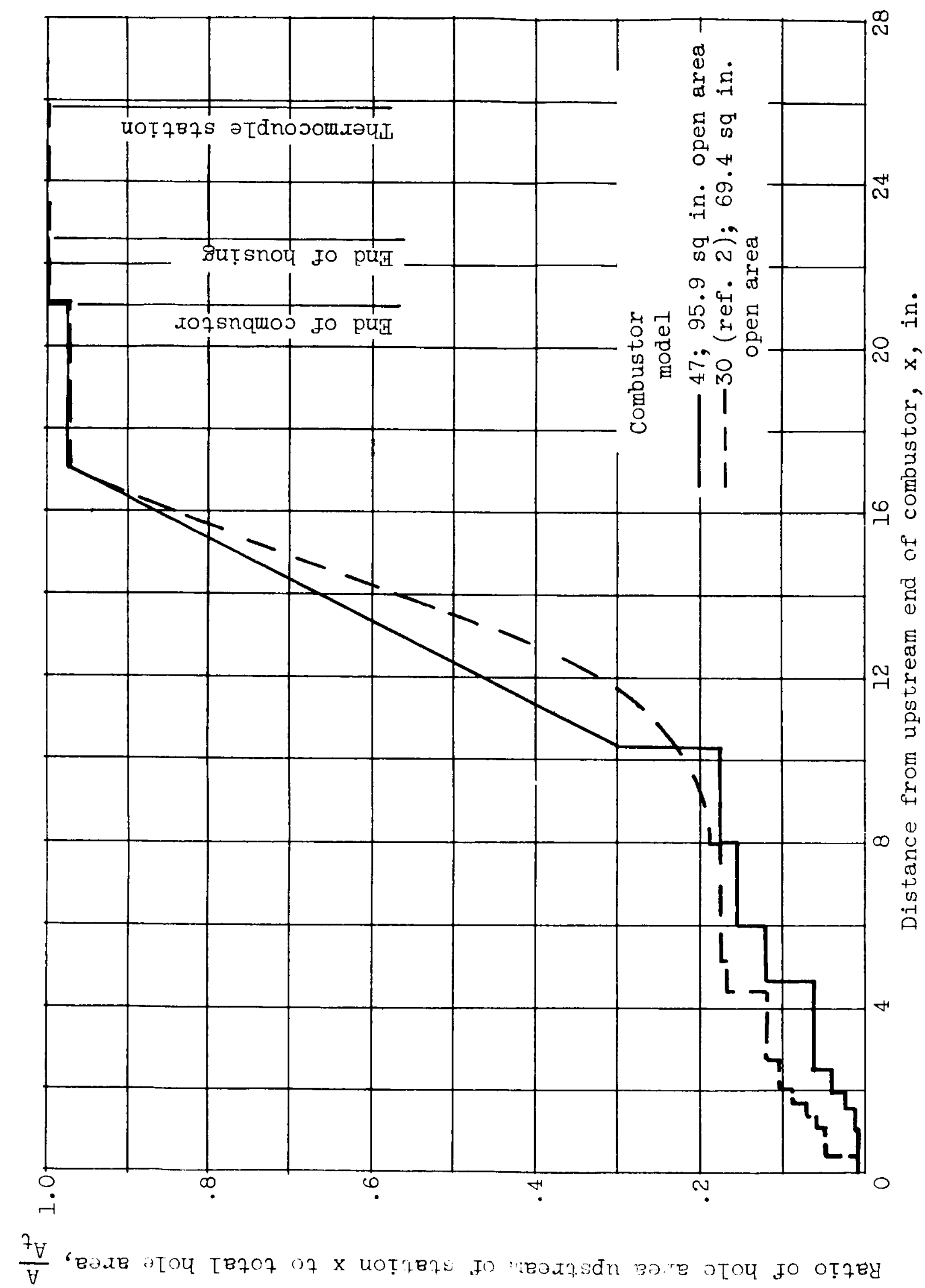
CH-4




(a) Wall pattern. (Dimensions are in inches.)

Figure 5. - Hole area.

[redacted]




(b) Distribution.

Figure 5. - Concluded. Hole area.

[redacted]

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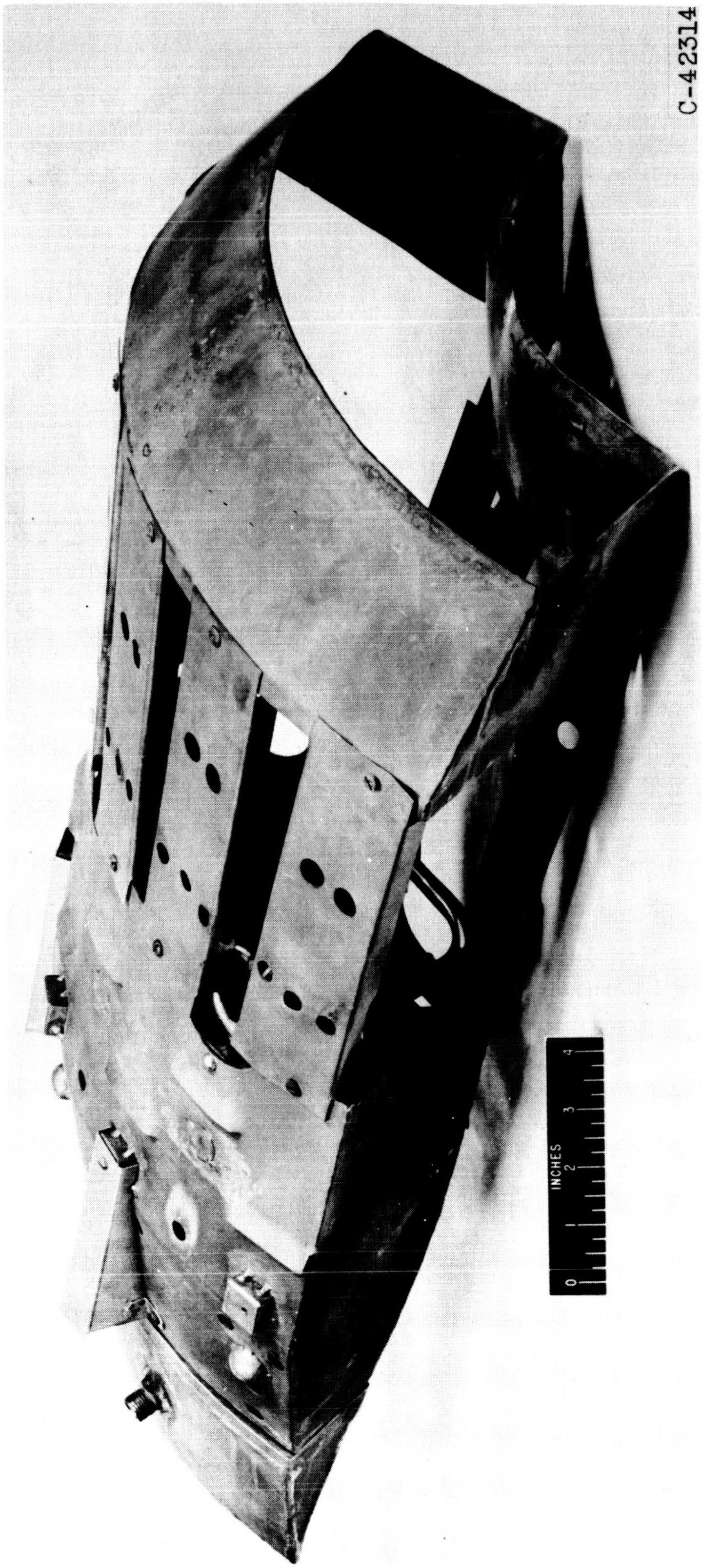
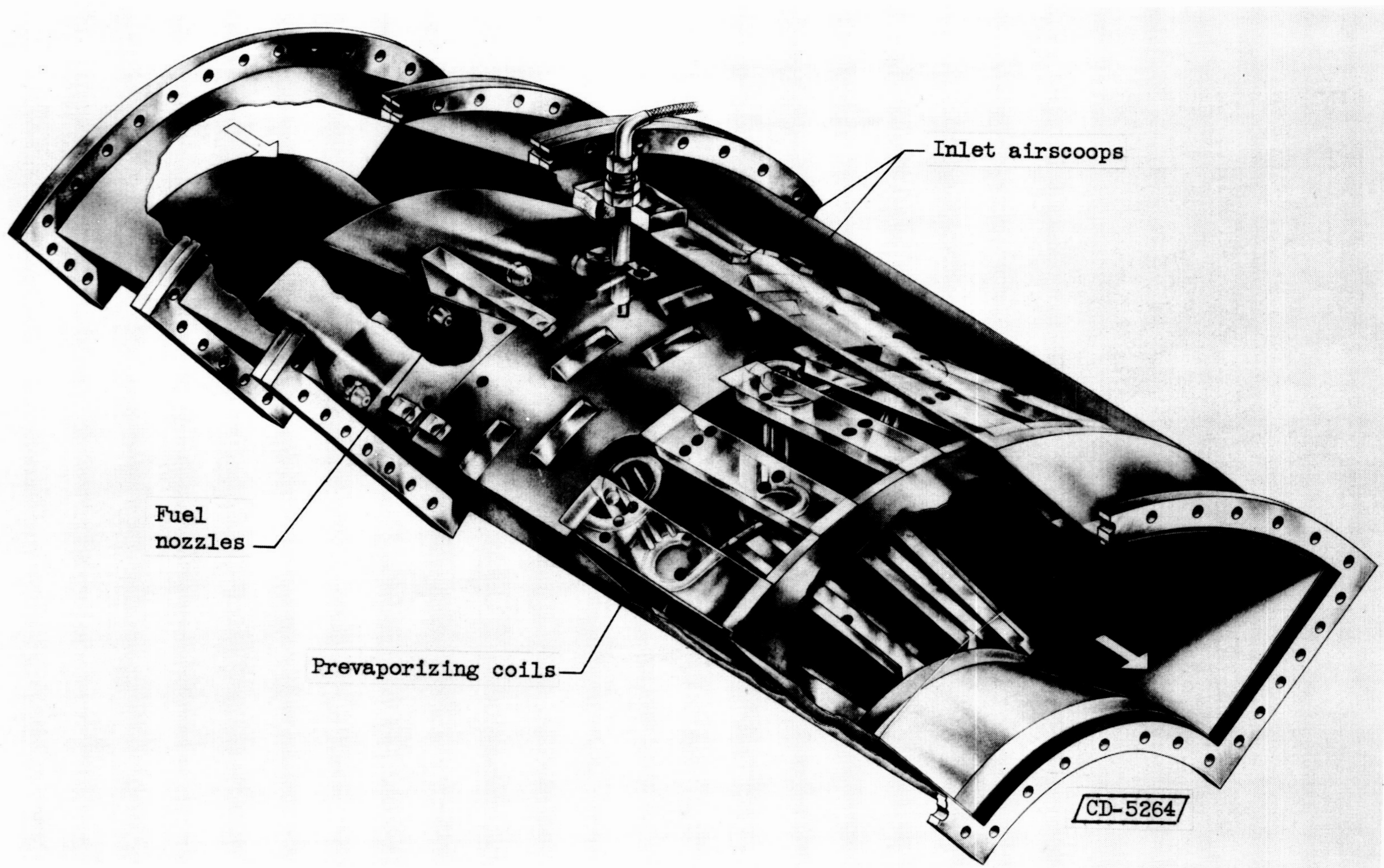
CH-4 back




(a) Combustor liner.

Figure 6. - One-quarter sector of annular prevaporizing combustor.




(b) Combustor liner assembled in housing.

Figure 6. - Concluded. One-quarter sector of annular prevaporizing combustor.

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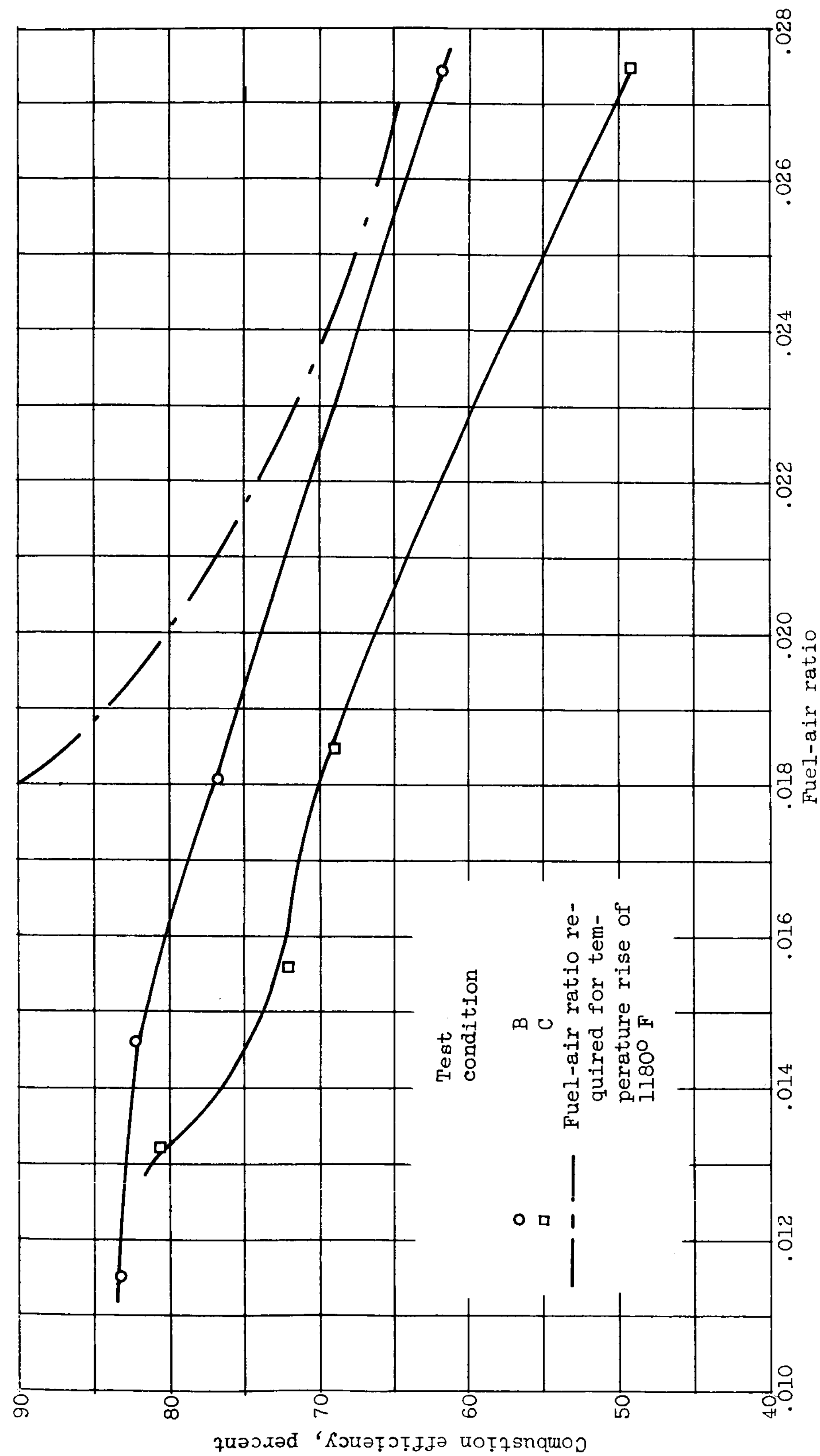


Figure 7. - Combustion efficiency of model 31K with propane fuel.

[redacted]

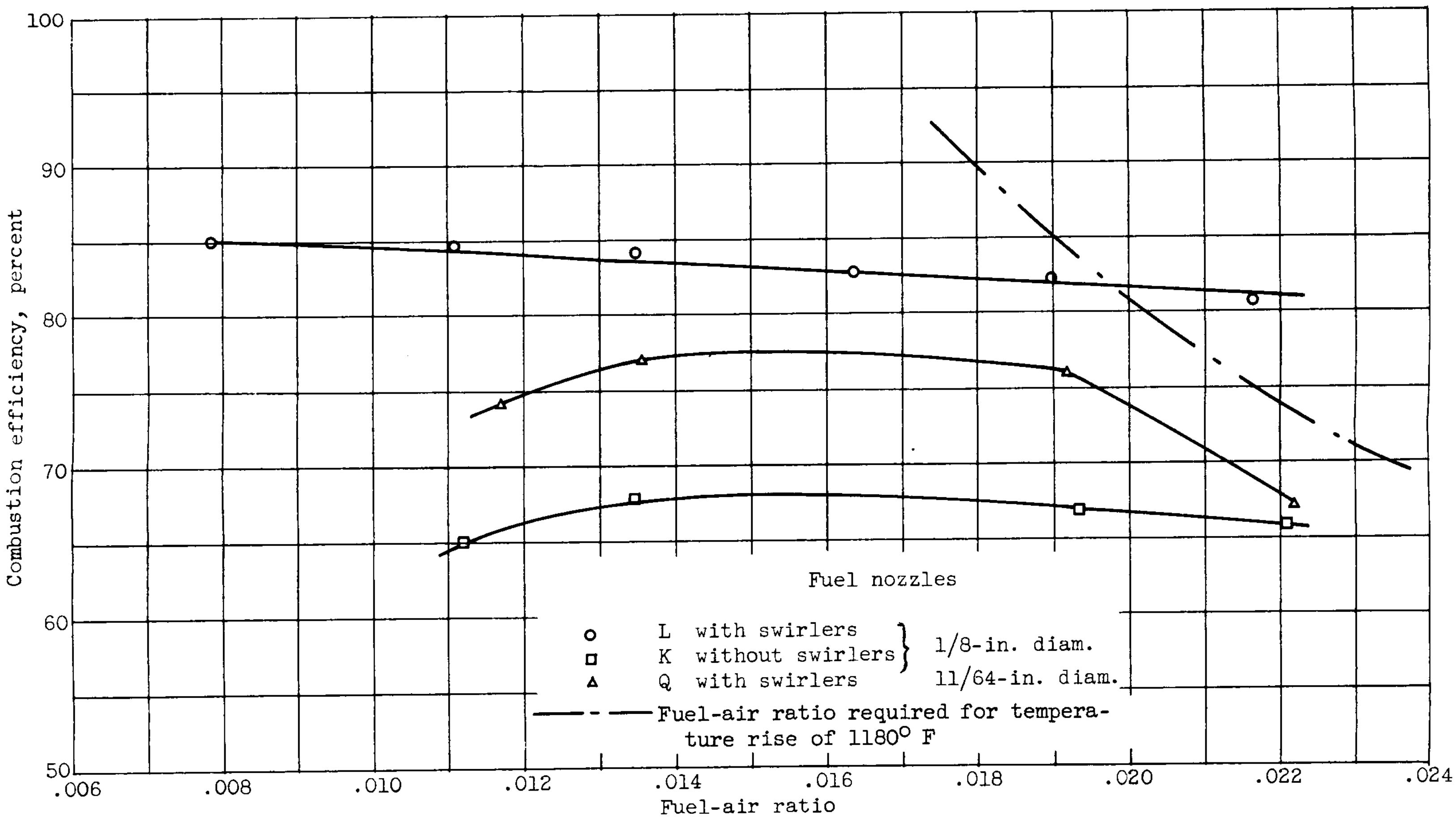


Figure 8. - Combustion efficiency of model 45 with propane fuel and fuel nozzles L, K, and Q at test condition C.

[redacted]

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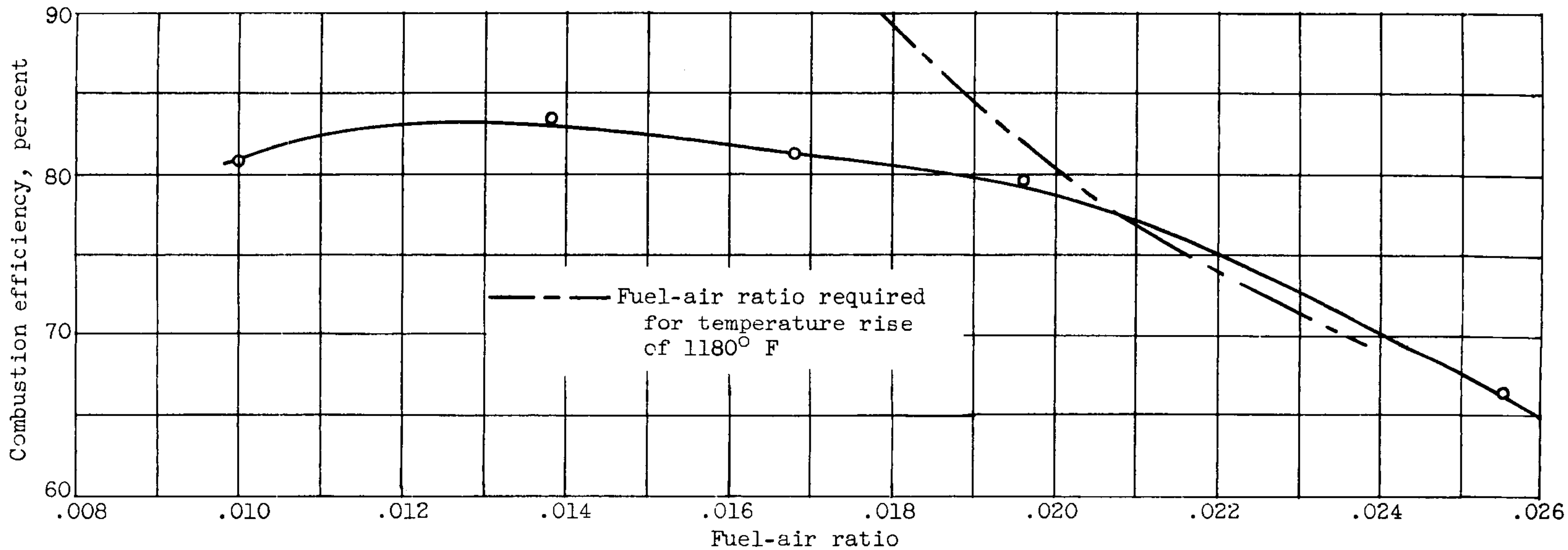
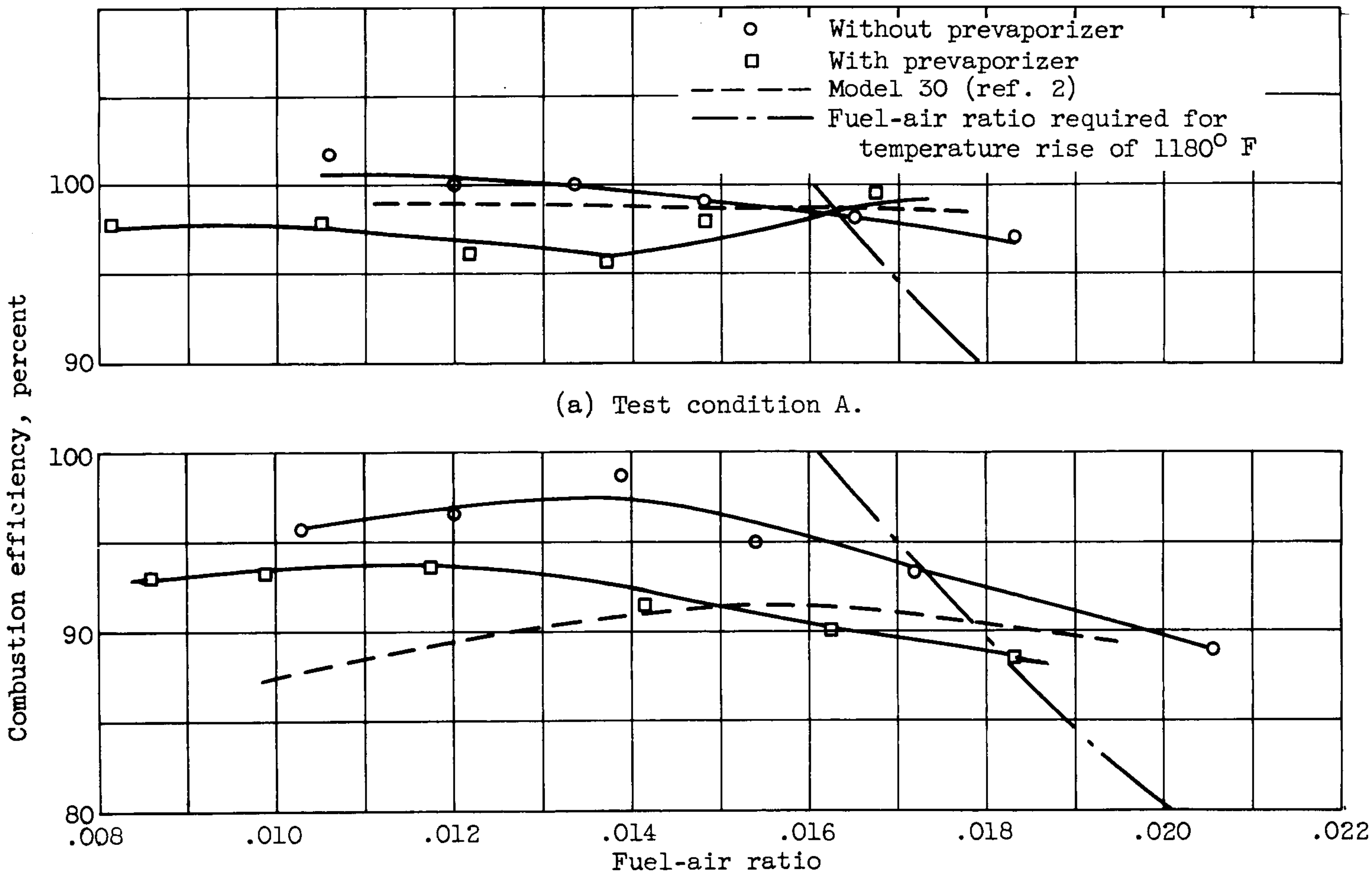



Figure 9. - Combustion efficiency of model 39P with propane fuel at test condition C.

[redacted]




(a) Test condition A.

(b) Test condition B.

Figure 10. - Combustion efficiency of prevaporizing combustor model 47L with and without prevaporizer installed and compared with model 30 (ref. 2); all data obtained with gaseous propane fuel at various test conditions.

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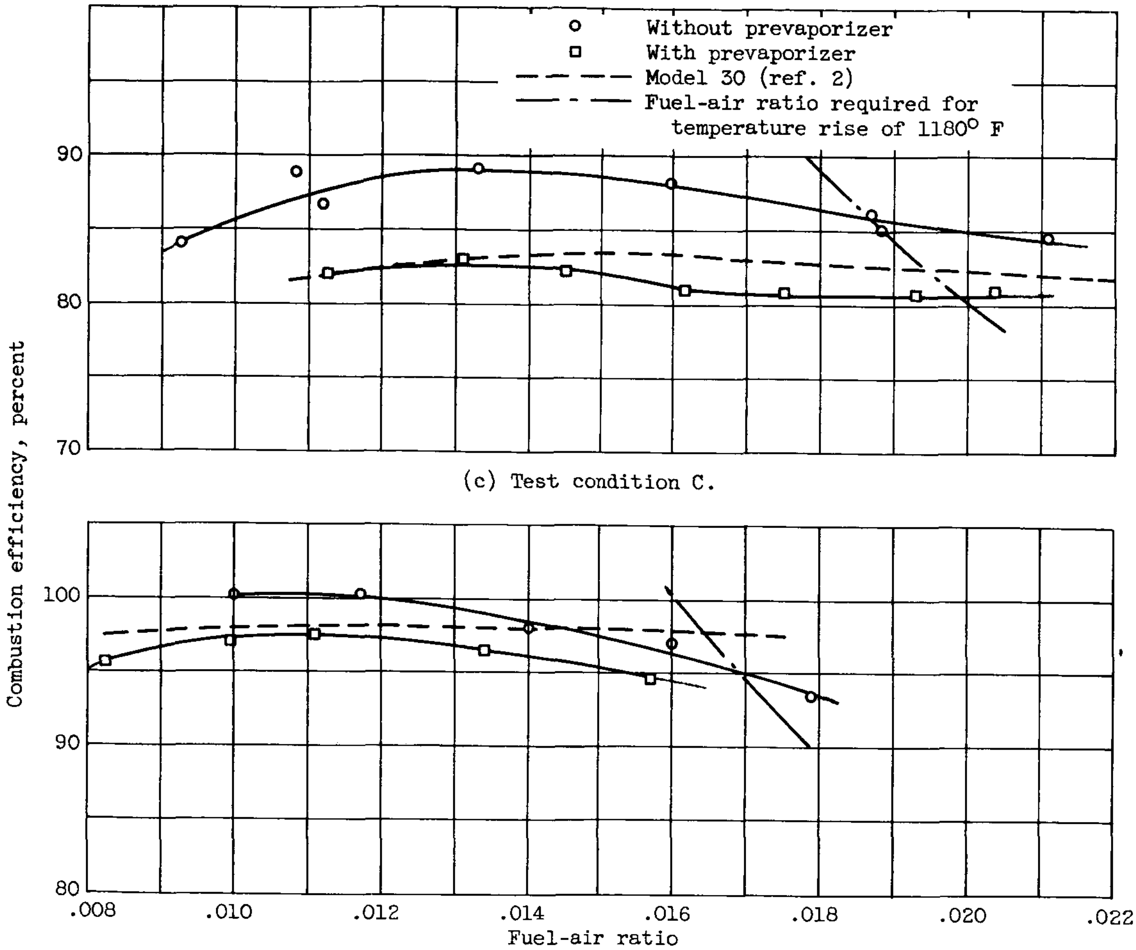
CH-5




(c) Test condition C.

(d) Test condition E.

Figure 10. - Concluded. Combustion efficiency of prevaporizing combustor model 47L with and without prevaporizer installed and compared with model 30 (ref. 2); all data obtained with gaseous propane fuel at various test conditions.

[redacted]

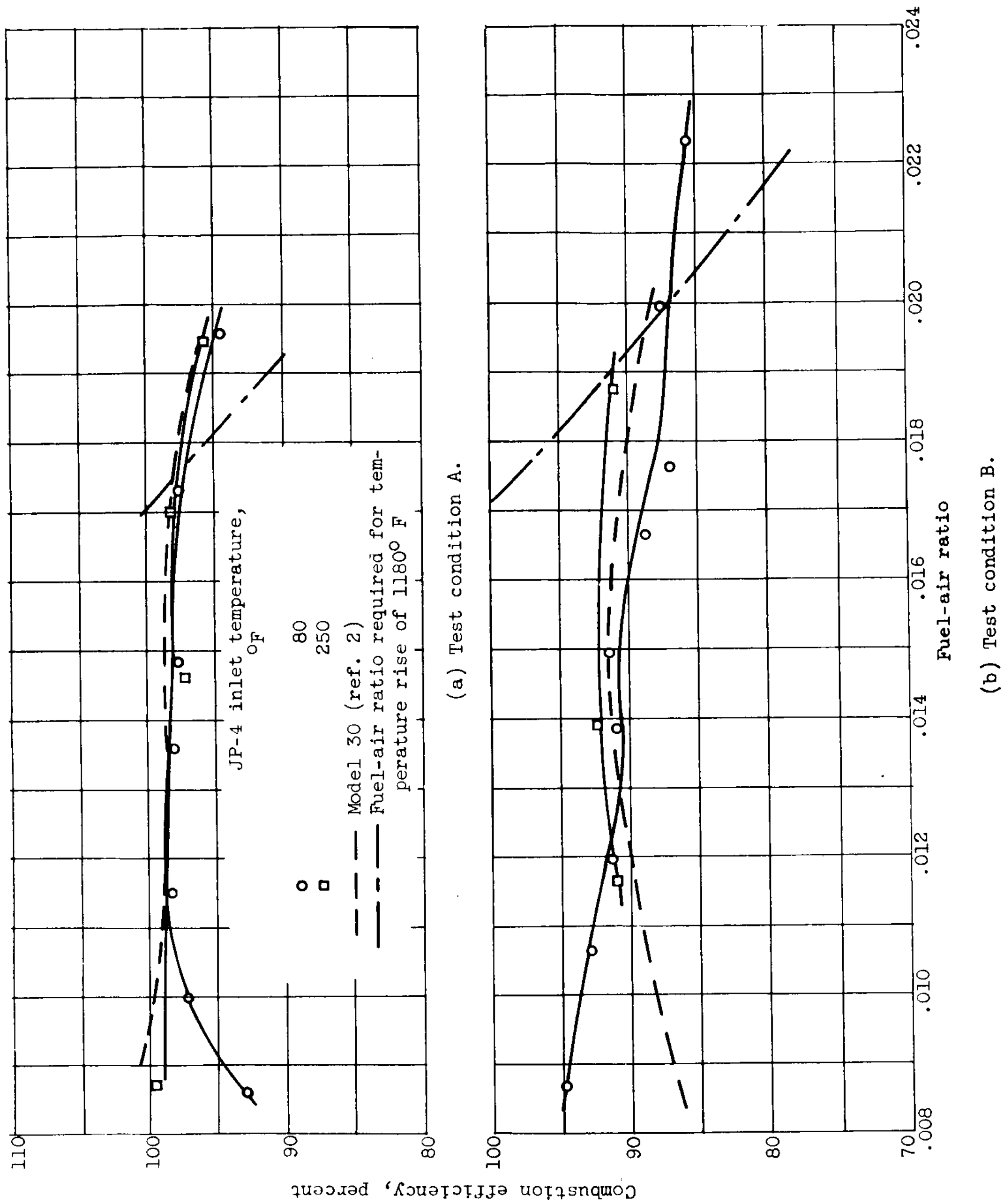



Figure 11. - Combustion efficiency of prevaporizing combustor model 47L with JP-4 fuel at two inlet temperature levels compared with data of model 30 (ref. 2).

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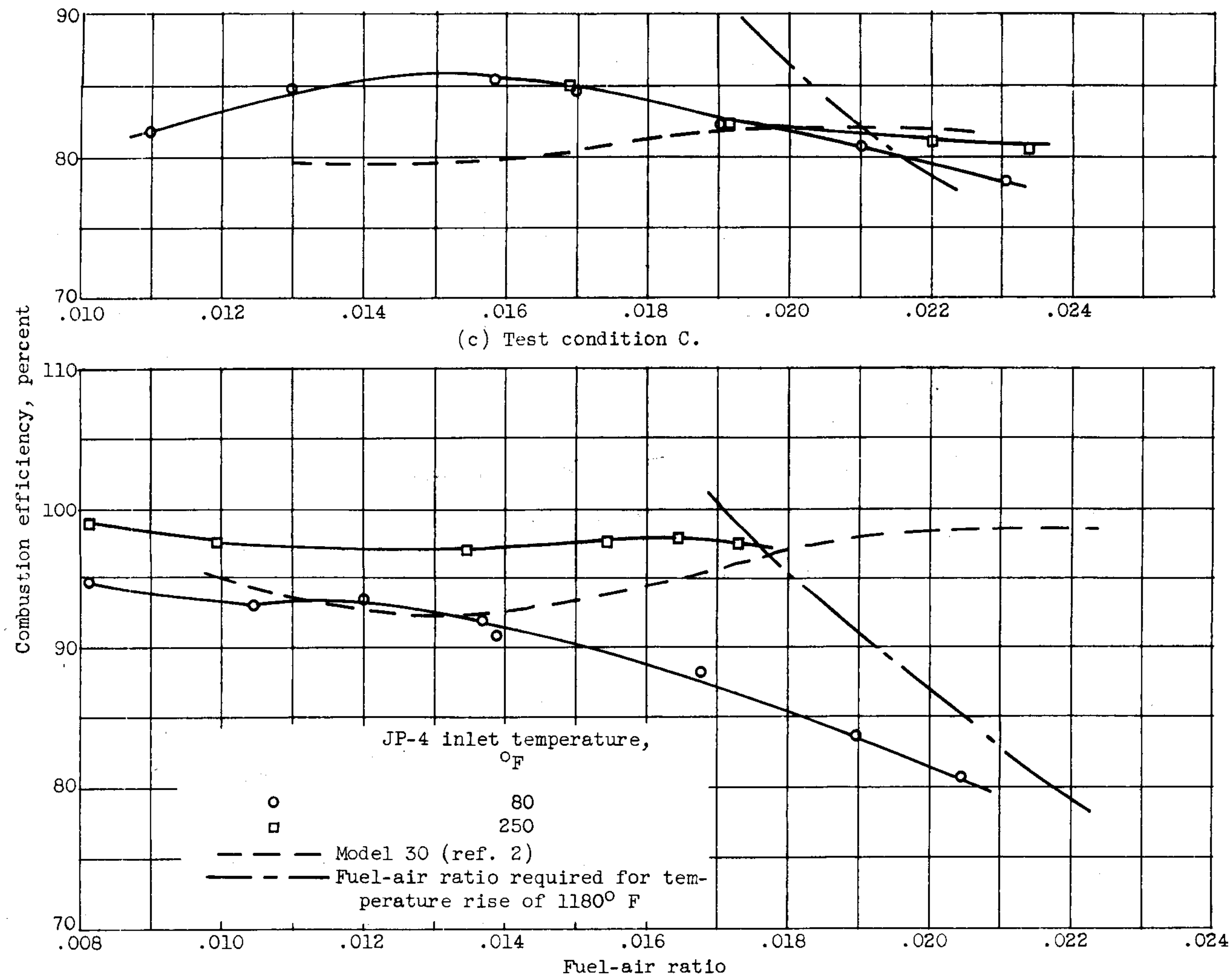


(d) Test condition E.

Figure 11. - Concluded. Combustion efficiency of prevaporizing combustor model 47L with P-4 fuel at two inlet temperature levels compared with data of model 30 (ref. 2).

[redacted]

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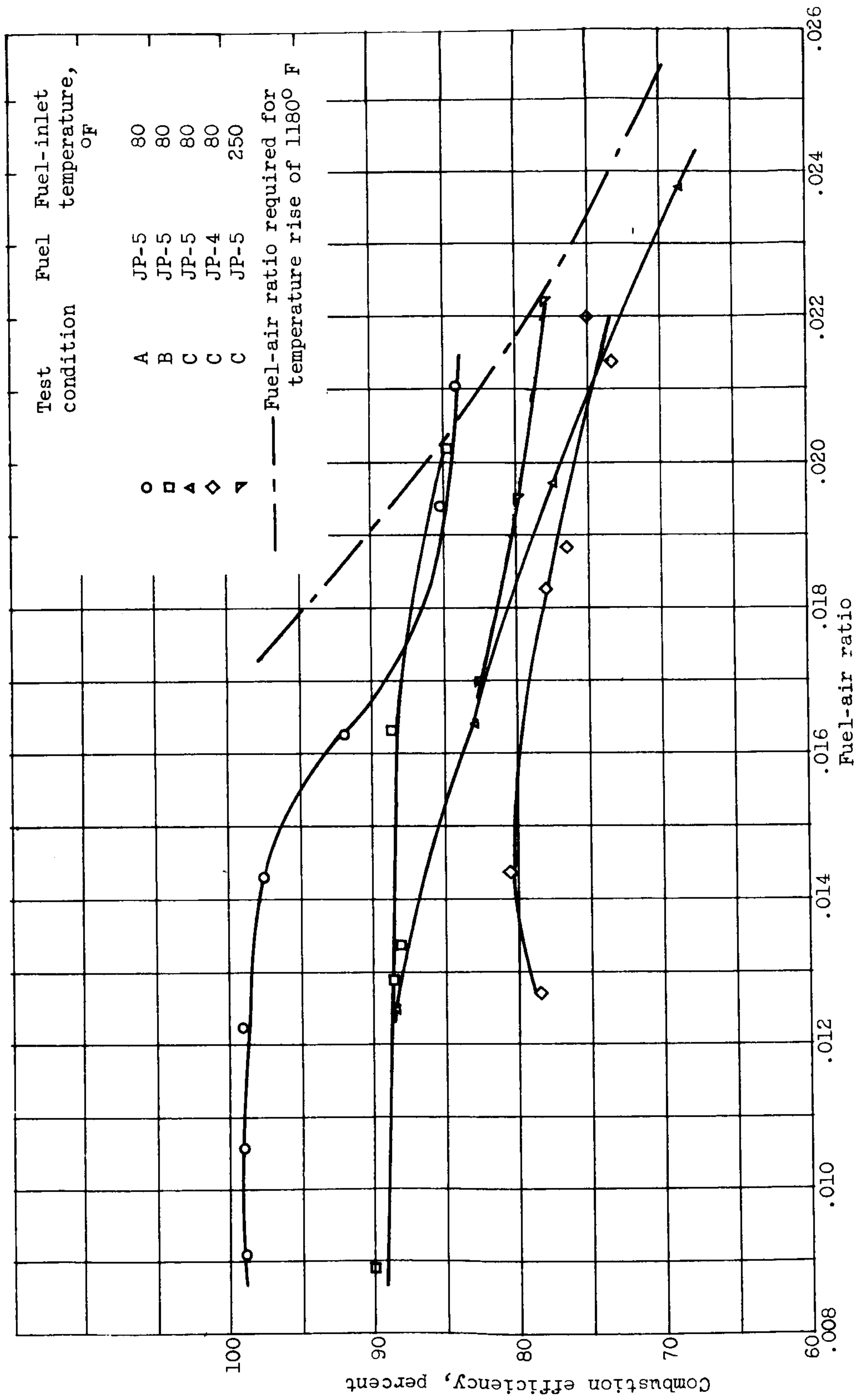


Figure 12. - Combustion efficiency of prevaporizing combustor model 47N with JP-5 fuel compared with JP-4 at test condition C.

[redacted]

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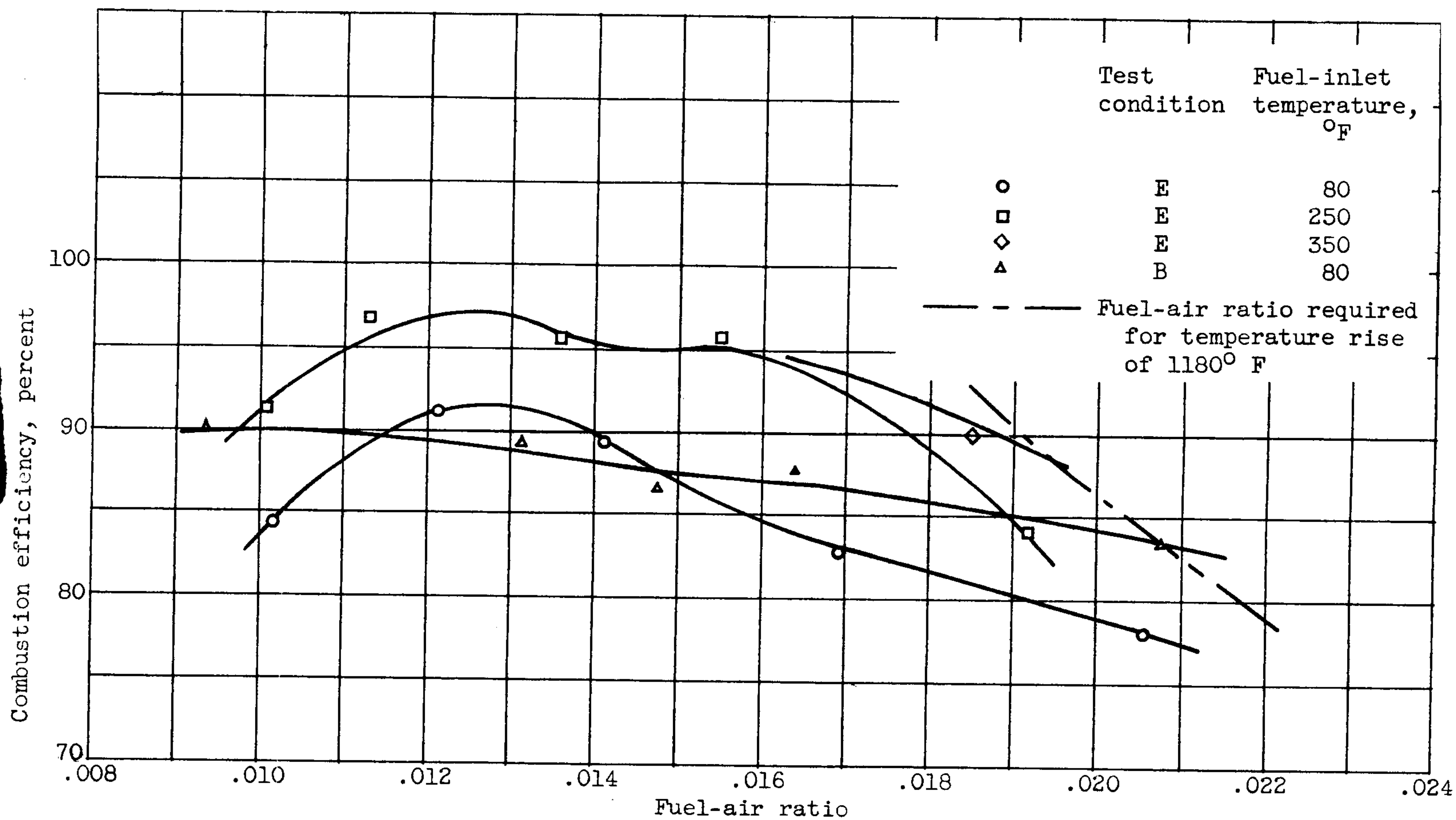


Figure 13. - Combustion efficiency of prevaporizing combustor model 47L with JP-5 fuel at three fuel inlet temperatures.

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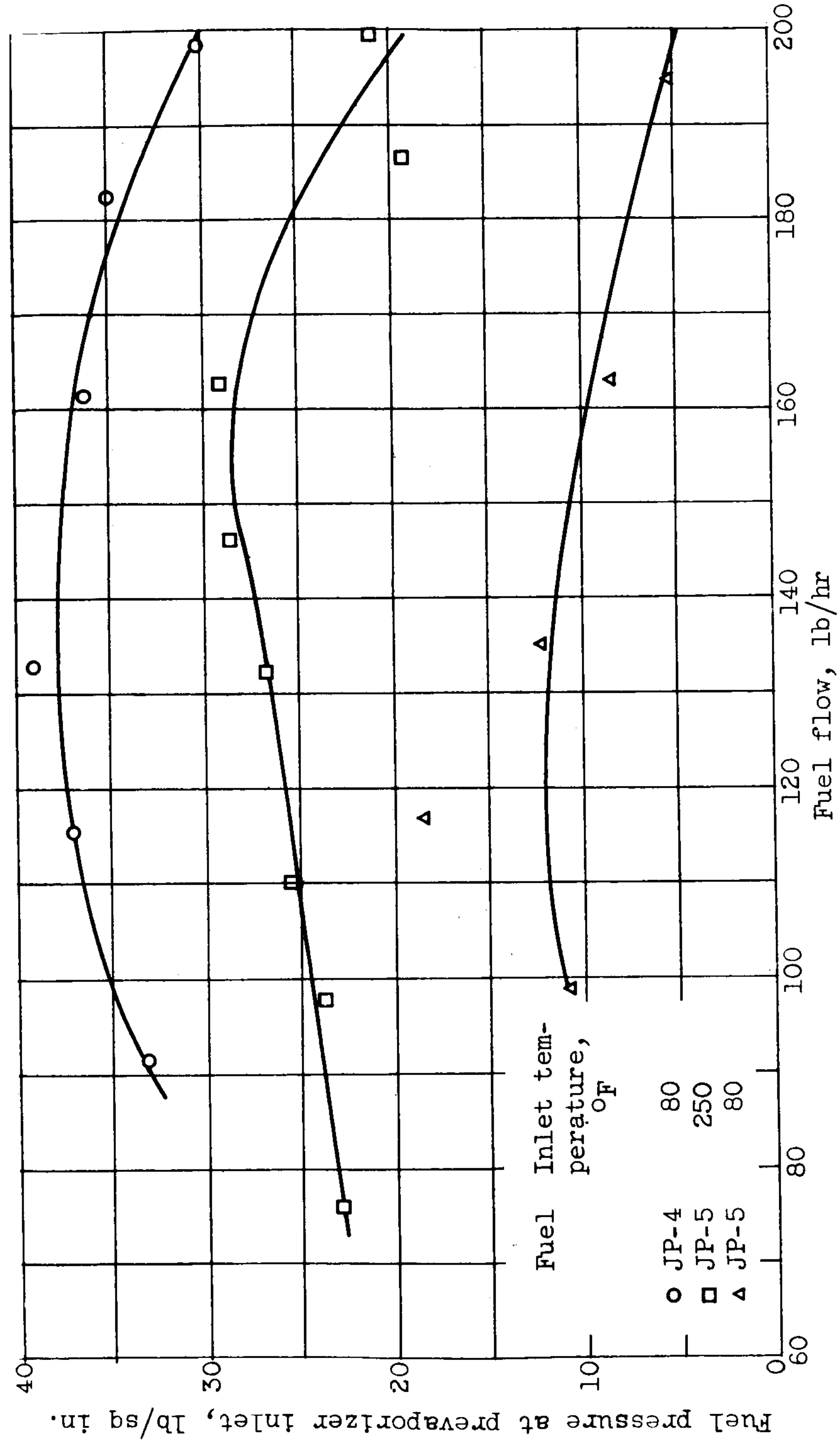


Figure 14. - Fuel pressure at prevaporizer inlet for fuel flows at test condition E.

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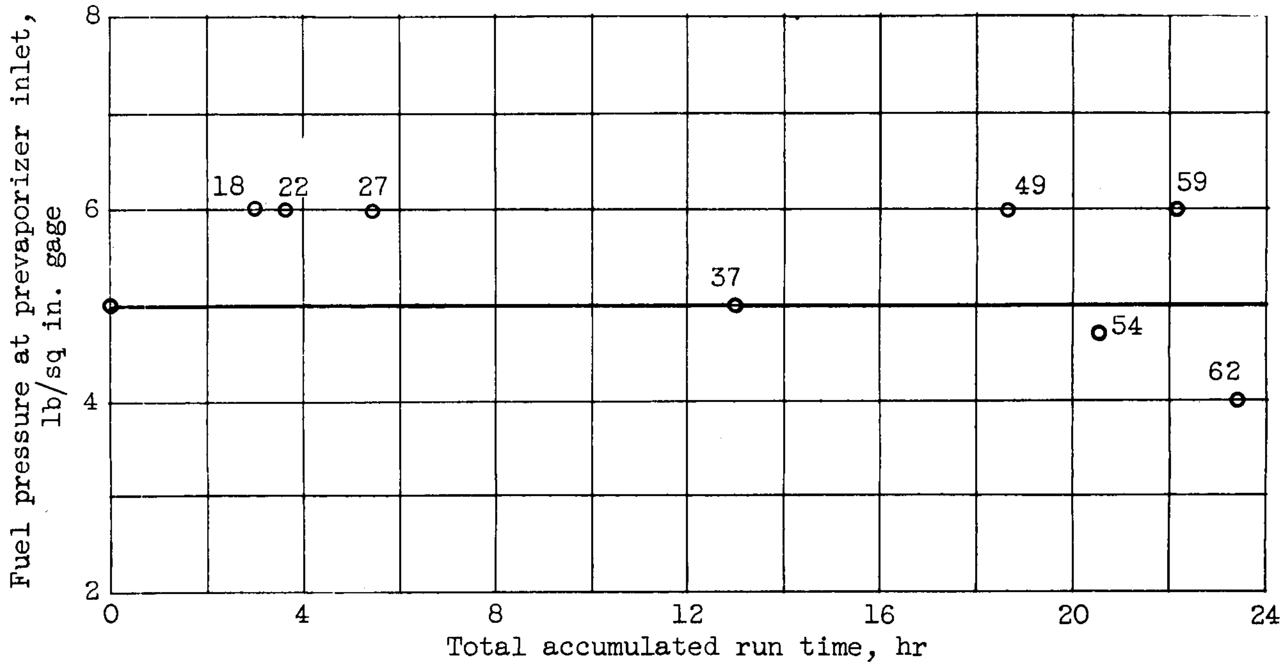


Figure 15. - Variation of fuel pressure at prevaporizer inlet with time for JP-5 fuel in model 47L. Inlet-fuel temperature, 90° F; outlet-fuel temperature, 600° to 700° F. Number of accumulated starts is indicated beside each data point.

[redacted]

[redacted]

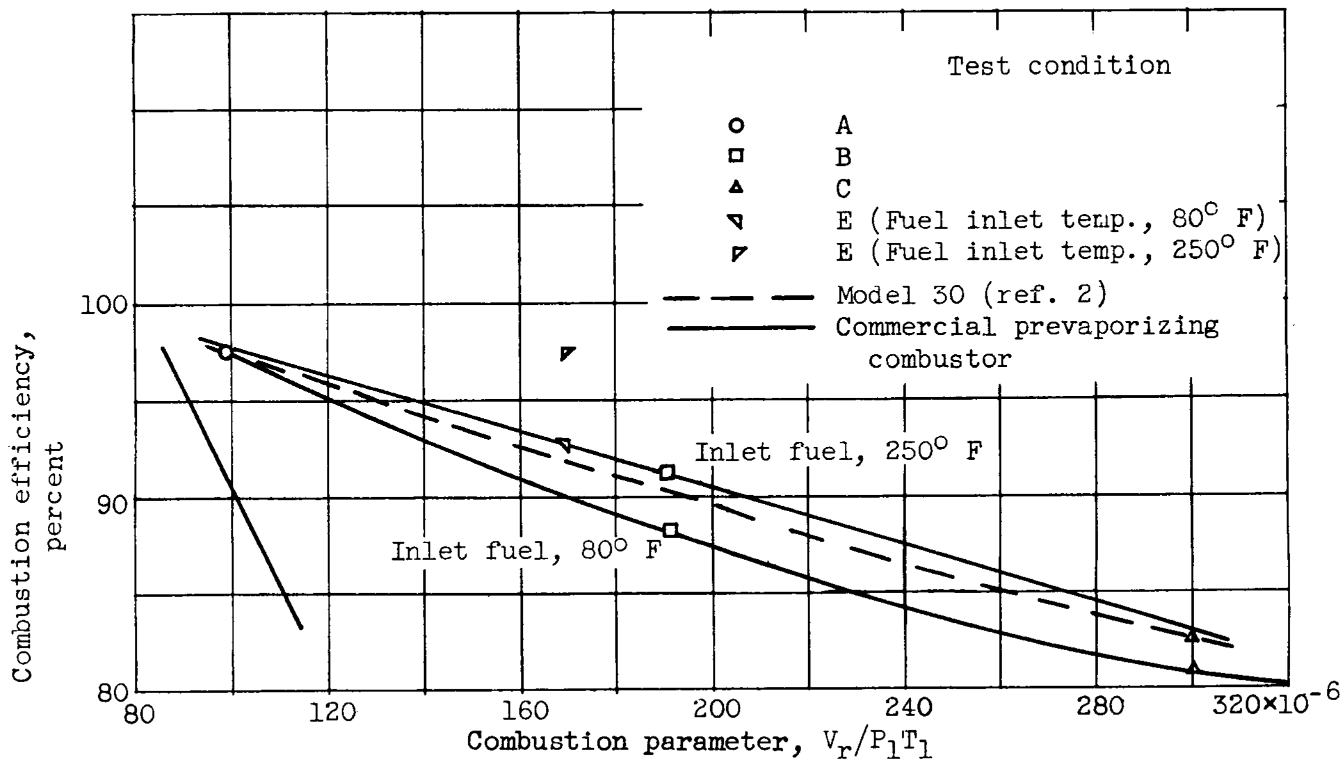


Figure 16. - Correlation of combustion-efficiency data of model 47L combustor compared with model 30 (ref. 2) at temperature rise level of 1180° F with JP-4 fuel.

[redacted]

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4180

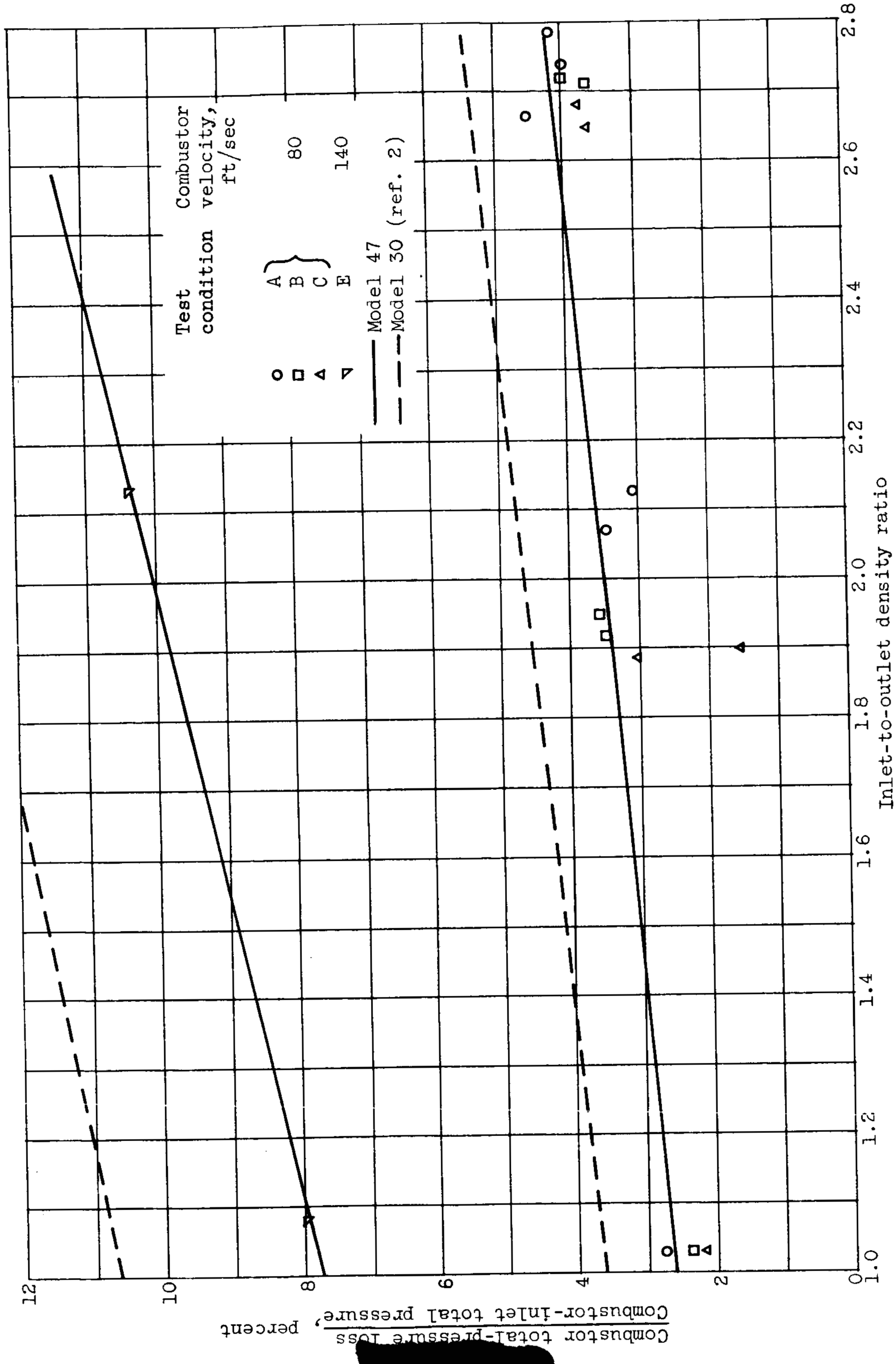


Figure 17. - Combustor pressure loss of model 47L combustor compared with model 30 (ref. 2).

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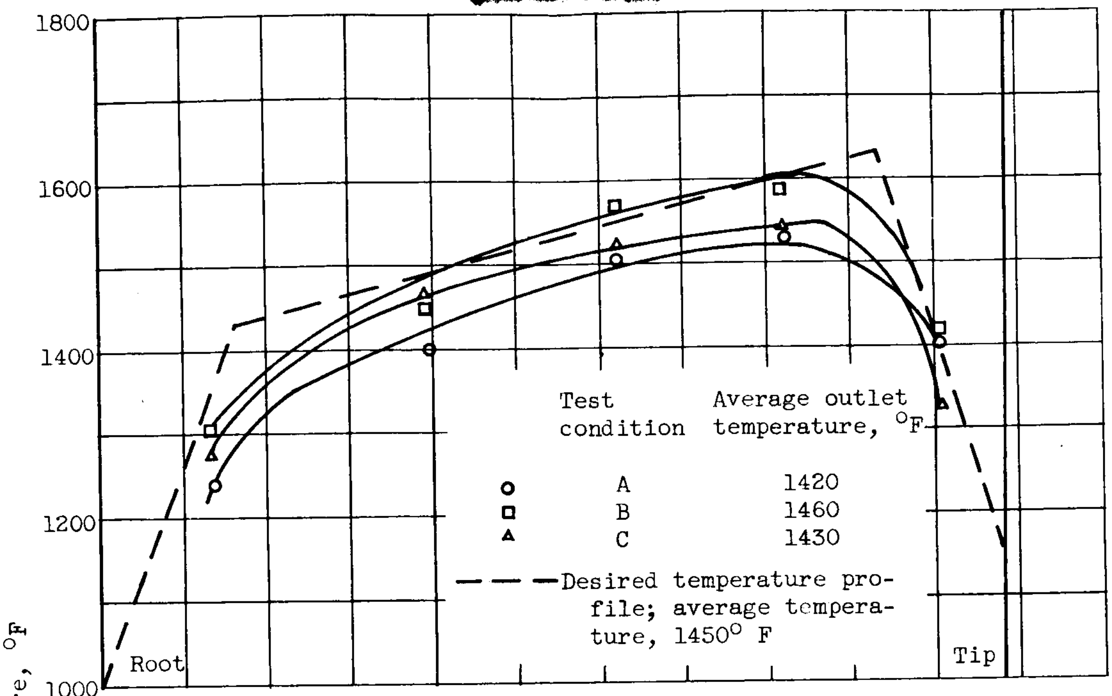
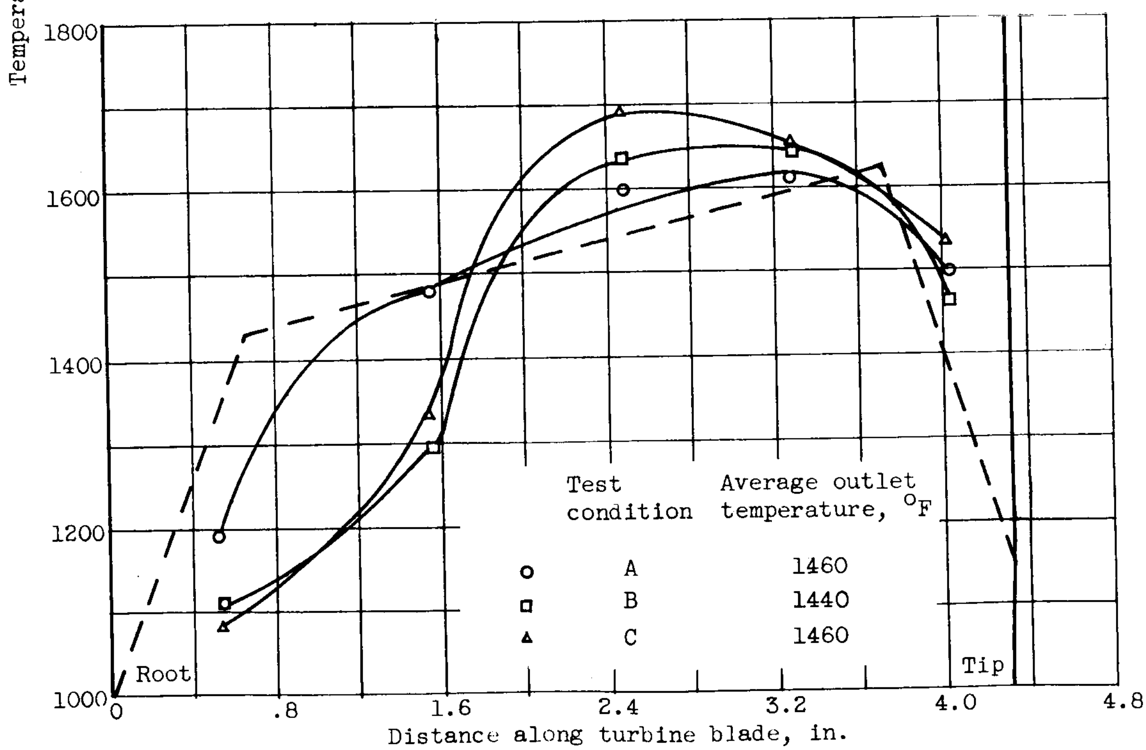



(a) Gaseous propane.




(b) Prevaporized liquid JP-4 fuel.

Figure 18. - Temperature profiles with combustor model 47L.

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